



Contents lists available at SciOpen

Food Science and Human Wellness

journal homepage: <https://www.sciopen.com/journal/2097-0765>

U-shaped, source-specific, and diversity-dependent associations of maternal protein intake with gestational hypertension

Hongjuan Liu¹, Xin Cao¹, Mingqi Ran¹, Guanyue Chen¹, Ziyu Chen¹, Shanshan Wang¹, Ting Xiong², Liping Hao^{1*}.

¹ Department of Nutrition and Food Hygiene, Hubei Key Laboratory of Food Nutrition and Safety and the Ministry of Education (MOE) Key Laboratory of Environment and Health, School of Public Health, Tongji Medical College, Huazhong University of Science and Technology, 13 Hangkong Rd, Wuhan, 430030, Hubei, China.

² Department of Nutrition and Food Hygiene, School of Public Health, Guangzhou Medical University, Xinzao, Panyu District, Guangzhou, 511436, China.

ABSTRACT: Gestational hypertension (GH) is a major pregnancy complication, but evidence regarding the influence of maternal protein intake remains limited. This study aimed to prospectively investigate the associations of protein quantity, sources, and diversity with GH risk in Chinese pregnant women. We included 2,160 singleton pregnant women from the Tongji Birth Cohort, with dietary intake assessed before 20 weeks of gestation using a validated food frequency questionnaire. Protein intake was energy-adjusted, and protein diversity scores were calculated. GH was defined according to Chinese and ACOG guidelines as new-onset hypertension after 20 weeks of gestation in previously normotensive women without proteinuria. Associations were analyzed using multivariable logistic regression and restricted cubic spline models. Stratified and joint analyses to explore potential effect modification. Total protein intake showed a U-shaped association with GH risk ($p_{\text{overall}} = 0.029$; $p_{\text{nonlinearity}} = 0.010$). Compared with the optimal intake of 56.61 g/day, both lower and higher intakes were linked to increased risk. Higher plant protein intake was inversely associated with GH risk (adjusted OR per SD increase, 0.68; 95% CI, 0.53–0.87), whereas higher animal protein intake was positively associated (adjusted OR per SD increase, 1.37; 95% CI, 1.06–1.76). Greater protein diversity was associated with lower GH risk. Joint analyses showed that women with high plant protein intake combined with high potassium or magnesium intake had the lowest GH risk. These findings indicate that maintaining optimal protein intake, favoring plant protein, and ensuring dietary protein diversity during first gestation may help prevent GH.

Keywords: Gestational hypertension; maternal diet; protein intake; protein sources; protein diversity; pregnancy; U-shaped association

1. Introduction

Hypertensive disorders of pregnancy (HDPs) remain a leading cause of maternal and perinatal morbidity and mortality, contributing to approximately 14% of maternal deaths worldwide^[1]. Gestational hypertension (GH), a subtype of HDPs, is defined as new-onset hypertension (systolic ≥ 140 mmHg or

*Corresponding author
haolp@mails.tjmu.edu.cn.

Received 15 October 2025
Received in revised form 14 December 2025
Accepted 15 January 2026

diastolic ≥ 90 mmHg) after 20 weeks in previously normotensive women without proteinuria^[2], and poses substantial maternal and fetal risks^[3]. Early-onset GH often progresses to preeclampsia or end-organ complications^[4, 5]. Even without progression, GH independently increases the risk of infant mortality, preterm birth, and small-for-gestational-age newborns^[6, 7], and confers elevated long-term cardiovascular risks for both mothers and offspring^[3, 8, 9]. These findings underscore the need for effective preventive strategies.

Preventive options for GH are limited, and pharmacological interventions raise fetal safety concerns^[10]. Dietary strategies represent promising, modifiable alternatives, with protein intake drawing particular interest^[11–13]. In non-pregnant populations, higher total or plant protein intake is generally linked to lower blood pressure^[14, 15]. However, evidence remains inconsistent, with some studies reporting null or even adverse associations^[16–19]. A recent umbrella review highlighted persisting uncertainties regarding total, animal, and plant protein intake on blood pressure^[20]. These mixed findings call for targeted research in pregnant women.

Evidence on maternal protein intake and GH is scarce and few studies differentiate protein sources. One trial of a high animal-protein, low-glycemic-index diet found no effect on blood pressure in pregnant women^[21], but its focus on overweight women limited generalizability. More recent population-based evidence indicates that plant and animal proteins may exert contrasting effects on maternal blood pressure after pregnancy^[22]. These observations suggest that both the quantity and source of protein consumed during pregnancy may influence GH risk.

Therefore, this study aimed to examine the associations between maternal protein intake during pregnancy and the risk of GH in a prospective Chinese birth cohort. We examine not only the overall quantity of protein consumed but also the contributions of different protein sources, and the diversity of protein intake. The findings may provide evidence to inform dietary strategies for the prevention of hypertensive disorders during pregnancy.

2. Materials and methods

2.1 Study design and participants

This study utilized data from the Tongji Birth Cohort (TJBC), a prospective cohort established in Wuhan, China, to examine how maternal nutrition and environmental exposures during pregnancy influence maternal and offspring health. Women eligible for inclusion were aged 18–45 years, carrying a singleton pregnancy, planning to deliver at designated hospitals, and willing to complete a structured face-to-face questionnaire during their initial antenatal visit. Detailed procedures of the TJBC have been reported previously^[23].

The study protocol was approved by the Ethics Review Committee of Tongji Medical College, Huazhong University of Science and Technology (No. 2021IEC[S044]). All participants provided written informed consent prior to enrollment.

Between 2018 and 2024, 2,749 pregnant women completed a semi-quantitative FFQ before 20 weeks of gestation, capturing habitual dietary intake prior to clinical diagnosis of GH. Participants were excluded if they had multiple pregnancies, miscarriage, stillbirth, implausible reported energy intake (<500 or $>4,000$ kcal/day), pre-existing chronic hypertension, or missing data on GH. After applying these criteria, 2,160 women remained for analysis (**Figure S1**).

2.2 Dietary protein intake assessment

Dietary intake was assessed before 20 weeks of gestation using a validated semi-quantitative FFQ, administered face-to-face by trained interviewers^[24]. The FFQ consisted of 74 food items assembled into 11 food groups: cereals, meats, fish, eggs, beans, vegetables, fruit, nuts, milk and milk products, beverages, and oils^[25]. The validity and reproducibility of the FFQ to evaluate nutrient and food intakes in Chinese pregnant women were assessed in a previous study^[24].

Participants reported the frequency and portion size of each item over the previous 4 weeks. Standard portion sizes were illustrated using food models and a photographic atlas. Nutrient intakes were calculated using the China Food Composition Database^[26] and a customized computer program.

Total protein intake was expressed in grams per day (g/d) and adjusted for total energy intake using the residual method^[27]. Protein intakes from different food sources were derived accordingly. Based on the FFQ food items, protein intake was classified into the following sources: refined grains, whole grains, legumes, nuts, vegetables, fruits, red meat, processed red meat, poultry, aquatic products, eggs, milk and milk powder, and fermented dairy products (**Table S1**).

Protein diversity was assessed using a protein source diversity score, reflecting the number of different protein-containing food sources consumed habitually during early pregnancy. For each predefined protein source, participants received one point if they reported consuming it at least once in the past month, and the total score was calculated as the sum of all sources consumed. Higher scores indicate greater protein diversity, intended to capture relatively stable dietary patterns.

2.3 Outcome assessment

GH was ascertained from antenatal clinic and hospital records and defined according to the Chinese Clinical Practice Guideline for Hypertension and Preeclampsia in Pregnancy (2020)^[28] and ACOG Practice Bulletin (2020)^[3]. Blood pressure was measured on the same arm using a validated digital sphygmomanometer (Omron HEM-7200; Omron Healthcare, Kyoto, Japan) after the participant had been seated and rested for 5–10 minutes, and a stable reading was recorded for analysis.

GH was defined as systolic blood pressure ≥ 140 mmHg or diastolic blood pressure ≥ 90 mmHg on two occasions at least 4 hours apart in previously normotensive women^[29]. Diagnoses were made during routine prenatal care after 20 weeks of gestation, consistent with standard clinical practice. All blood pressure records documented in antenatal care booklets and hospital systems were reviewed and cross-checked to confirm GH status.

2.4 Covariates

Baseline sociodemographic, clinical, and lifestyle information was obtained through structured face-to-face interviews by trained investigators and from medical records. Data included maternal age, education, family income per capita, pre-pregnancy height and weight, smoking, alcohol consumption, coffee and tea intake, regular exercise habits, sleep duration, work status during pregnancy, family history of hypertension, gestational diabetes mellitus (GDM) status, nutritional supplement use and other relevant factors.

Pre-pregnancy Body mass index (BMI) was calculated as $BMI = \text{weight (kg)} / [\text{height (m)}]^2$. Education level was categorized as <10, 10–16, and ≥ 16 years according to completed schooling years. Family monthly income per capita was categorized as <5000, 5000–10000, and ≥ 10000 CNY per month. Regular exercise before pregnancy was defined as engaging in structured physical activity at least once per week over a sustained period. Smoking, alcohol use, and coffee or tea consumption were all defined as occurring at least once per week before pregnancy. GDM diagnosed using the 75-g oral glucose tolerance test at 24–28 weeks according to the IADPSG/WHO 2010 criteria^[30].

2.5 Statistical analysis

Continuous variables were assessed for normality using the Shapiro–Wilk test. Normally distributed variables are presented as mean $\pm$ standard deviation (SD) and compared using independent-samples *t* tests, while non-normally distributed variables were expressed as median (interquartile range) and compared between groups using the Mann–Whitney *U* test. Categorical variables were presented as counts and percentages, and differences between groups were evaluated using the chi-square test.

Protein intake was analyzed as both a continuous variable and in quartiles (Q1 as reference). Dose–response relationships between protein intake and GH risk were examined using restricted cubic spline (RCS) models with four knots at the 5th, 35th, 65th, and 95th percentiles, following Harrell's recommendations. The median protein intake served as the reference. To identify potential threshold effects, two-piecewise logistic regression (segmented regression) was performed, with turning points determined by log-likelihood ratio tests using the segmented R package. Linear associations across quartiles were estimated using multivariable logistic regression, and trends were tested by modeling the median value of each quartile as a continuous variable.

Covariates related to protein intake and GH identified in previous studies were included as potential confounders in the analyses. The regression models were structured as follows: Crude model, not adjusted for any variables; Adjusted model, adjusted for maternal age, gravidity, parity, pre-pregnancy BMI, education and income levels, smoking, alcohol use, and coffee or tea intake before pregnancy, family history of hypertension, regular exercise before pregnancy, GDM status, night-time sleep duration during pregnancy, employment status during pregnancy, nutritional supplement use, energy-adjusted fat and carbohydrate intakes, dietary fiber, cholesterol, sodium and potassium intakes, and gestational weeks at FFQ administration. Pre-pregnancy BMI and baseline lifestyle behaviors were adjusted to represent habitual metabolic status and long-term exposures prior to pregnancy, whereas variables that are more likely to vary

during pregnancy, including supplement use, sleep duration, and employment status, were adjusted using contemporaneous measures.

For protein source analyses, plant proteins (refined grains, whole grains, legumes, nuts, vegetables, fruits) and animal proteins (unprocessed red meat, processed red meat, poultry, aquatic foods, eggs, milk and milk powder, and fermented dairy products) were examined separately using similar approaches. Protein diversity scores, reflecting the number of distinct protein-containing food sources habitually consumed during early gestation, were analyzed using multivariable logistic regression to evaluate their associations with GH risk.

Multicollinearity among dietary variables and covariates was assessed using variance inflation factors (VIFs); variables with VIF >10 were reviewed and either combined or removed.

To further explore potential joint associations between protein intake and dietary minerals, potassium, magnesium, calcium, and sodium intakes were categorized into high and low groups according to cohort-specific median values. Joint associations were examined across four exposure categories: low protein–low mineral, low protein–high mineral, high protein–low mineral, and high protein–high mineral, with the low protein–low mineral group serving as the reference. Models used for joint analyses were the same as the adjusted models described above, ensuring consistency with main analyses.

Sensitivity analyses were performed to assess the robustness of the findings. First, additional models were fitted with further adjustment for total energy intake to assess whether associations were independent of overall energy consumption. Second, protein intake was alternatively expressed as a percentage of total energy intake (%E) instead of energy-adjusted grams per day.

Stratified analyses were performed to assess whether the associations between protein intake and GH risk differed across subgroups. Maternal age, pre-pregnancy BMI, dietary fiber intake, and cholesterol intake were dichotomized at their median values, while GDM status and family history of hypertension were treated as binary variables. Multiplicative interaction terms between protein intake and stratification factors were tested with likelihood ratio tests.

All statistical tests were two-sided, with $P < 0.05$ considered statistically significant. Analyses were performed using R version 4.2.2 (R Foundation for Statistical Computing, Vienna, Austria ; <https://www.R-project.org/>), with the rms package for RCS models and segmented package for piecewise regression.

3. Results

3.1 Characteristics of the participants

A total of 2,160 pregnant women were included in the final analysis (**Table 1**). The median gestational age at FFQ administration was 13.7 weeks (interquartile range: 12.7–15.6 weeks). Baseline characteristics were comparable between the overall cohort and participants included in the final analysis (**Table S2**), suggesting minimal selection bias. Women who developed GH had higher pre-pregnancy weight and BMI and a higher prevalence of a family history of hypertension compared with those who did not develop GH

(all $P < 0.05$). The prevalence of GDM was also higher in the GH group ($p = 0.020$). No significant differences were observed for maternal age, ethnicity, education, income, lifestyle factors, or total energy intake between the two groups. Notably, median plant protein intake was lower among women with GH compared with those without GH ($p = 0.032$), whereas total and animal protein intake did not differ significantly.

Table 1. Baseline characteristics of participants by gestational hypertension (GH) status¹

	ALL (N=2160)	Non-GH (N=2060)	GH (N=100)	P value
Maternal characteristics				
Maternal age at enrollment, y	29.00 (27.00-31.00)	29.00 (27.00-31.00)	28.00 (26.00-31.25)	0.865
Ethnicity (Han Chinese), yes	2108 (97.59%)	2011 (97.62%)	97 (97.00%)	0.732
Pre-pregnancy weight, kg	54.00 (49.00-60.00)	54.00 (49.00-60.00)	56.20 (51.25-62.88)	0.002
Height, cm	161.00 (158.00-165.00)	161.00 (158.00-165.00)	160.00 (158.00-165.00)	0.475
Pre-pregnancy BMI, kg/m ²	20.77 (19.12-22.63)	20.74 (19.07-22.58)	22.21 (20.22-23.54)	<0.001
Educational levels, schooling years				0.052
<10	165 (7.64%)	152 (7.38%)	13 (13.00%)	
10-16	917 (42.45%)	871 (42.28%)	46 (46.00%)	
≥16	1078 (49.91%)	1037 (50.34%)	41 (41.00%)	
Family monthly income per capita, CNY				0.194
<5000	307 (14.21%)	288 (13.98%)	19 (19.00%)	
5000-10000	1096 (50.74%)	1043 (50.63%)	53 (53.00%)	
≥10000	757 (35.05%)	729 (35.39%)	28 (28.00%)	
GDM				0.020
yes	367 (16.99%)	341 (16.55%)	26 (26.00%)	
no	1793 (83.01%)	1719 (83.45%)	74 (74.00%)	
Primiparous, yes	1628 (75.37%)	1554 (75.44%)	74 (74.00%)	0.747
Primigravida, yes	1211 (56.06%)	1157 (56.17%)	54 (54.00%)	0.404
Drinking before pregnancy, yes	146 (6.76%)	142 (6.89%)	4 (4.00%)	0.357
Smoking before pregnancy, yes	60 (2.78%)	59 (2.86%)	1 (1.00%)	0.524
Tea before pregnancy, yes	387 (17.92%)	373 (18.11%)	14 (14.00%)	0.362
Coffee before pregnancy, yes	357 (16.53%)	339 (16.46%)	18 (18.00%)	0.789
Nighttime sleep hours	9.00 (8.00-9.50)	9.00 (8.00-9.50)	9.00 (8.00-9.50)	0.910
Family history of hypertension, yes	563 (26.06%)	528 (25.63%)	35 (35.00%)	0.049
Regular exercise before pregnancy, yes	840 (38.89%)	799 (38.79%)	41 (41.00%)	0.735
Work status during pregnancy, yes	1143 (52.9%)	1098 (53.3%)	45 (45.00%)	0.128
Nutrition supplement use, yes	2120 (98.15%)	2023 (98.20%)	97 (97.00%)	0.429
Dietary intake				
Gestational week at FFQ, wks	13.71 (12.71-15.57)	13.71 (12.71-15.57)	13.64 (12.86-15.50)	0.778
Total energy (kcal/day)	1817.74 (1505.33-2135.89)	1817.74 (1505.03-2136.73)	1813.64 (1506.90-2121.04)	0.396
Protein (g/d)	51.90 (42.09-62.51)	51.92 (42.17-62.59)	50.40 (40.56-59.98)	0.308
Plant protein	35.57 (28.96-41.96)	35.64 (29.04-42.06)	32.97 (26.61-39.62)	0.032
Animal protein	18.31 (12.05-26.13)	18.33 (12.13-26.12)	18.07 (11.47-26.55)	0.753
Fat (g/d)	62.02 (46.67-79.23)	61.92 (46.56-79.25)	63.25 (49.16-79.12)	0.621
Carbohydrate (g/d)	262.76 (216.69-313.82)	263.56 (216.83-314.64)	254.27 (199.93-300.04)	0.107

Dietary fiber intake (g/d)	12.70 (10.10-15.78)	12.70 (10.14-15.78)	12.41 (9.58-15.80)	0.797
Dietary cholesterol intake (mg/d)	279.17 (157.32-381.46)	277.62 (157.75-381.37)	300.00 (135.31-384.57)	0.990
Dietary potassium intake (mg/d) ²	2049.70 (1655.71-2539.71)	2050.24 (1658.90-2539.71)	2019.83 (1551.96-2539.73)	0.635
Dietary sodium intake (mg/d) ²	350.62 (263.23-453.28)	350.65 (263.11-454.96)	348.70 (268.07-435.26)	0.846
Dietary calcium intake (mg/d) ²	482.94 (357.94-624.18)	483.11 (357.67-626.31)	467.54 (370.64-590.47)	0.604
Dietary magnesium intake (mg/d) ²	288.17 (233.47-346.17)	288.27 (233.20-346.17)	281.16 (233.88-346.03)	0.895

¹ Continuous variables are expressed as median (interquartile range) and categorical variables as n (%), unless otherwise indicated. Differences between groups were assessed using the Mann–Whitney U test for continuous variables and the χ^2 test for categorical variables.

GH, gestational hypertension; BMI, body mass index; FFQ, food frequency questionnaire.

² Mineral intakes (potassium, sodium, calcium, and magnesium) were estimated based on food items reported in the semi-quantitative Food Frequency Questionnaire (FFQ) only.

3.2 Total protein intake and risk of GH

The dose–response relationship between dietary protein intake and GH risk is illustrated in **Figure 1**. A significant U-shaped relationship was observed (p -overall = 0.029, p -nonlinear = 0.010). Piecewise logistic regression identified a threshold of 56.61 g/d, indicating opposite directions of association on either side of this threshold (**Table 2**). Below this threshold, each 10 g/d increase in total protein was associated with a 50% lower risk of GH (adjusted OR = 0.50; 95% CI: 0.31–0.83). Above the threshold, higher total protein intake was associated with an increased risk of GH (adjusted OR = 1.49; 95% CI: 1.02–2.14) (**Table 2**).

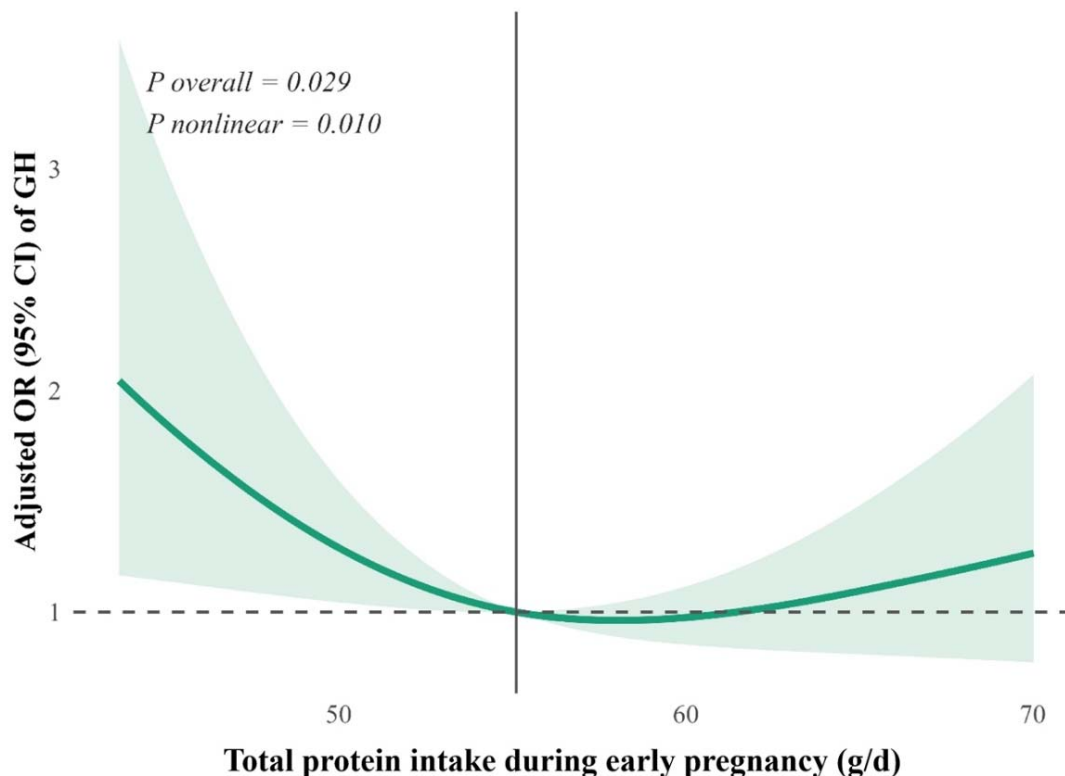


Figure 1. Dose–response association between total dietary protein intake and GH risk.

The association was modeled using restricted cubic splines with 4 knots placed at the 5th, 35th, 65th, and 95th percentiles of protein intake. The solid green line represents the estimated odds ratio (OR), and the light green shaded area represents the 95% confidence interval (CI). Models were adjusted for maternal age, pre-pregnancy BMI, education and income levels, parity, tea and coffee intake before pregnancy, alcohol and cigarette use before pregnancy, family history of hypertension, regular exercise before pregnancy, GDM status, night-time sleep duration during pregnancy, employment status during pregnancy, nutritional supplement use, energy-adjusted fat and carbohydrate intakes, dietary fiber, cholesterol, sodium and potassium intakes, and gestational weeks at FFQ administration. BMI, body mass index; FFQ, food frequency questionnaire; GDM, gestational diabetes mellitus.

Table 2. Associations of maternal total protein intake with the risk of GH ¹

	Cut-off points value ² (g/d)	Dietary protein intake (per 10g increment)					
		< cut-off point			≥ cut-off point		
		N	OR (95% CI)	<i>P value</i>	N	OR (95% CI)	<i>P value</i>
GH							
Crude model	56.61	1248	0.63 (0.43, 0.94)	0.019	912	1.53 (1.09, 2.09)	0.005
Adjusted model	56.61	1248	0.50 (0.31, 0.83)	0.006	912	1.49 (1.02, 2.14)	0.031

¹ Crude model: unadjusted. Adjusted Model: adjusted for maternal age, gravidity, parity, pre-pregnancy BMI, education and income levels, smoking, alcohol use, and coffee or tea intake before pregnancy, family history of hypertension, regular exercise before pregnancy, GDM status, night-time sleep duration during pregnancy, employment status during pregnancy, nutritional supplement use, energy-adjusted fat and carbohydrate intakes, dietary fiber, cholesterol, sodium and potassium intakes, and gestational weeks at FFQ administration.

² Based on piecewise logistic regression analyses, a cut-off point of 56.61 g/d was identified as the threshold at which the association between total protein intake and GH risk changed.

Abbreviations: BMI, body mass index; FFQ, food frequency questionnaire; GDM, gestational diabetes mellitus.

3.3 Plant and animal protein intake and risk of GH

Higher plant protein intake was inversely associated with GH risk (**Table 3**). After multivariable adjustment, women in the highest quartile of plant protein intake had a significantly lower risk of GH compared with those in the lowest quartile (adjusted OR = 0.28; 95% CI: 0.13–0.60; *p* for trend = 0.001). Each 1-SD increase in plant protein was associated with a 32% lower risk (adjusted OR = 0.68; 95% CI: 0.53–0.87). RCS analysis indicated a linear inverse association between plant protein intake and GH risk (*p* -overall = 0.010; *p* -nonlinear = 0.130) (**Figure 2A**).

Table 3. Associations of plant and animal protein intakes with the risk of GH ¹

		Crude model		Adjusted model	
	Cases/Total	OR (95% CI)	P-value	OR (95% CI)	P-value
Plant protein (g/d)					
Q1 (<32.26)	36/540	Ref	-	Ref	-
Q2 (32.26-35.75)	28/540	0.77 (0.46, 1.27)	0.304	0.75 (0.43, 1.31)	0.311
Q3 (35.76-39.43)	25/540	0.68 (0.40, 1.15)	0.149	0.68 (0.38, 1.21)	0.189
Q4 (>39.43)	11/540	0.29 (0.15, 0.58)	<0.001	0.28 (0.13, 0.60)	0.001
P for trend			<0.001		0.001
Per SD increment		0.70 (0.57, 0.86)	<0.001	0.68 (0.53, 0.87)	0.003
Animal protein (g/d)					
Q1 (<14.14)	23/540	Ref	-	Ref	-
Q2 (14.14-19.00)	26/540	1.14 (0.64, 2.02)	0.661	0.99 (0.53, 1.84)	0.974
Q3 (19.01-24.47)	18/540	0.78 (0.41, 1.45)	0.427	0.63 (0.31, 1.27)	0.194
Q4 (>24.47)	33/540	1.46 (0.85, 2.53)	0.172	1.19 (0.60, 2.37)	0.624
P for trend			0.251		0.715
Per SD increment		1.25 (1.03, 1.51)	0.024	1.37 (1.06, 1.76)	0.015

¹ Crude model: unadjusted. Adjusted model: adjusted for maternal age, gravidity, parity, pre-pregnancy BMI, education and income levels, smoking, alcohol use, and coffee or tea intake before pregnancy, family history of hypertension, regular exercise before pregnancy, GDM status, night-time sleep duration during pregnancy, employment status during pregnancy, nutritional supplement use, energy-adjusted fat and carbohydrate intakes, dietary fiber, cholesterol, sodium and potassium intakes, and gestational weeks at FFQ administration. Plant and animal proteins were mutually adjusted in each model. BMI, body mass index; FFQ, food frequency questionnaire; GDM, gestational diabetes mellitus.

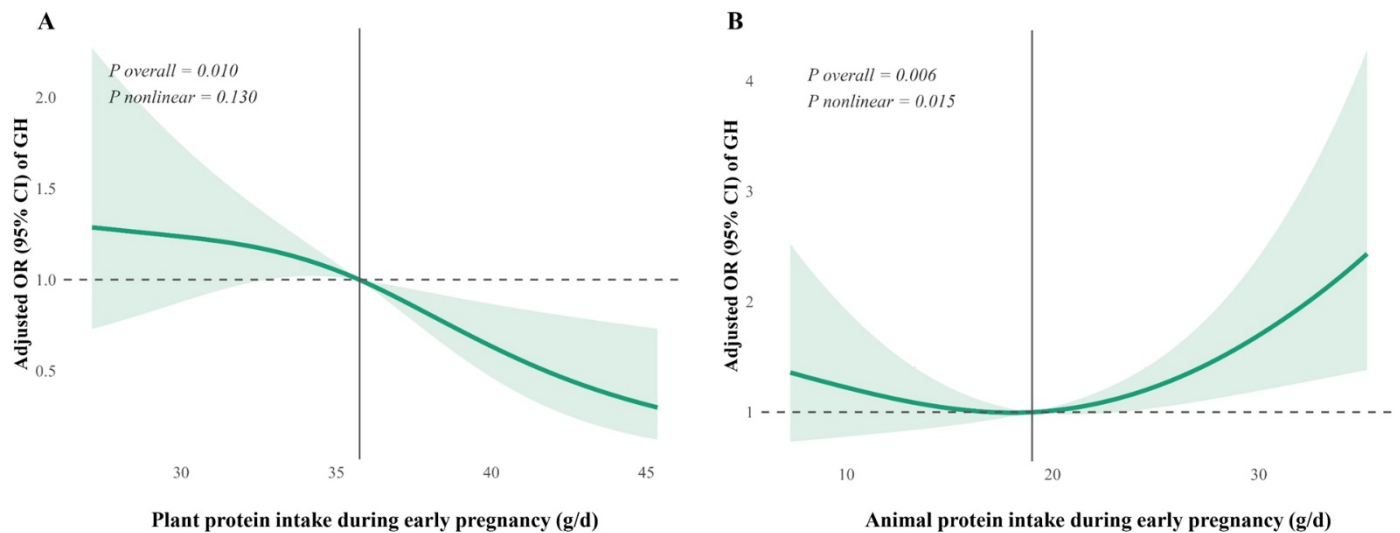


Figure 2. Associations between plant and animal protein intake and GH risk.

(A) Plant protein; (B) Animal protein. Associations were modeled using restricted cubic splines with 4 knots placed at the 5th, 35th, 65th, and 95th percentiles of intake. The solid green line represents the estimated odds ratio (OR), and the light green shaded area represents the 95% confidence interval (CI). Plant and animal protein intakes were mutually adjusted in the models, along with other covariates listed in Figure 1. BMI, body mass index; FFQ, food frequency questionnaire; GDM, gestational diabetes mellitus.

In contrast, higher animal protein intake was associated with an increased risk of GH. In adjusted models, each 1-SD increase in animal protein intake was associated with a 34% higher risk of GH (adjusted OR = 1.34; 95% CI: 1.06–1.76) (**Table 3**). RCS analysis revealed a J-shaped relationship, with GH risk increasing at higher levels of animal protein intake ($p_{\text{overall}} = 0.006$; $p_{\text{nonlinear}} = 0.015$) (**Figure 2B**).

3.4 Individual protein sources and risk of GH

Associations between protein intake from specific food sources and the risk of GH are presented in **Table S3** and **Figure 3**. Processed red meat protein intake was strongly positively associated with GH risk. Compared with women in the lowest quartile, those in the highest quartile had higher risk of GH (adjusted OR = 3.44; 95% CI: 1.81–6.53), with a clear dose–response relationship across quartiles ($p_{\text{for trend}} < 0.001$).

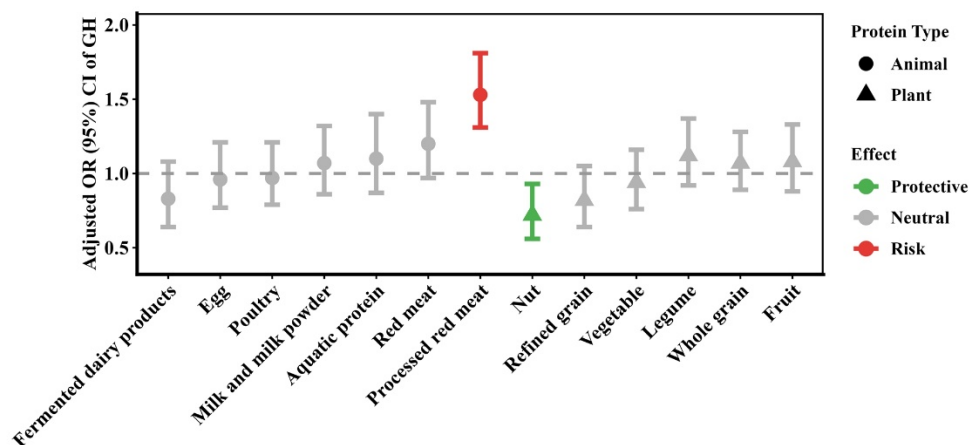


Figure 3. Associations of protein intake from different food sources with GH risk.

The forest plot presents odds ratios (ORs) and 95% confidence intervals (CIs) for protein intake from various food sources.

Estimates are shown per 1 standard deviation (SD) increment of energy-adjusted protein intake. Green markers indicate significant inverse associations (protective), red markers indicate significant positive associations (increased risk), and grey markers indicate non-significant associations. Models were mutually adjusted for different protein sources and adjusted for covariates listed in Figure 1.

Nut-derived protein intake was inversely associated with GH risk. Each 1-SD increase was associated with a 27% lower risk (adjusted OR = 0.73; 95% CI: 0.56–0.95). Quartile-based analyses showed a borderline inverse trend (p for trend = 0.060). No significant associations were observed between GH risk and protein intake from aquatic products, poultry, dairy products, eggs, legumes, vegetables, fruits, or grains after adjustment for potential confounders (Table S3).

3.5 Protein variety score and risk of GH

Higher protein variety scores were associated with lower GH risk (Table 4). Compared with women in the lowest quartile (Q1), those in Q3 and Q4 had a 50% and 51% lower risk of GH, respectively (adjusted OR = 0.50; 95% CI: 0.27–0.92 for Q3; adjusted OR = 0.49; 95% CI: 0.26–0.91 for Q4), with a significant trend across quartiles (p for trend = 0.018).

Table 4. Associations of protein source variety with the risk of GH¹

Protein variety score	Cases/Total	Crude model		Adjusted model	
		OR (95% CI)	P-value	OR (95% CI)	P-value
Q1 (4-9)	33/540	Ref	-	Ref	-
Q2 (9-10)	28/540	0.84 (0.50, 1.41)	0.510	0.79 (0.46, 1.35)	0.391
Q3 (10-11)	19/540	0.56 (0.31, 1.00)	0.049	0.50 (0.27, 0.92)	0.027
Q4 (11-13)	20/540	0.59 (0.33, 1.04)	0.070	0.49 (0.26, 0.91)	0.024
P for trend			0.046		0.018
Per SD increment		0.91 (0.74, 1.10)	0.318	0.87 (0.70, 1.09)	0.221

¹ Crude model: unadjusted. Adjusted model: adjusted for maternal age, gravidity, parity, pre-pregnancy BMI, education and income levels, smoking, alcohol use, and coffee or tea intake before pregnancy, family history of hypertension, regular exercise before pregnancy, GDM status, night-time sleep duration during pregnancy, employment status during pregnancy, nutritional supplement use, energy-adjusted fat and carbohydrate intakes, dietary fiber, cholesterol, sodium and potassium intakes, and gestational weeks at FFQ administration. BMI, body mass index; FFQ, food frequency questionnaire; GDM, gestational diabetes mellitus.

3.6 Effect modification by dietary minerals

Multiplicative interaction analyses were conducted to evaluate whether dietary mineral intakes modified the association between protein intake and GH risk. In joint analyses, the inverse association between plant protein intake and GH was more pronounced among women with higher intakes of potassium or magnesium (Figure 4). Compared with women with both low plant protein and low mineral intake, those with high plant protein combined with high magnesium intake had the lowest risk of GH (adjusted OR = 0.39; 95% CI: 0.22–0.71). A similar pattern was observed for high plant protein intake in combination with high potassium intake (adjusted OR = 0.41; 95% CI: 0.22–0.74). No clear effect modification was observed for sodium or calcium intake, and the associations between total or animal protein intake and GH were not materially modified by any of the examined minerals (Table S4 and S5).

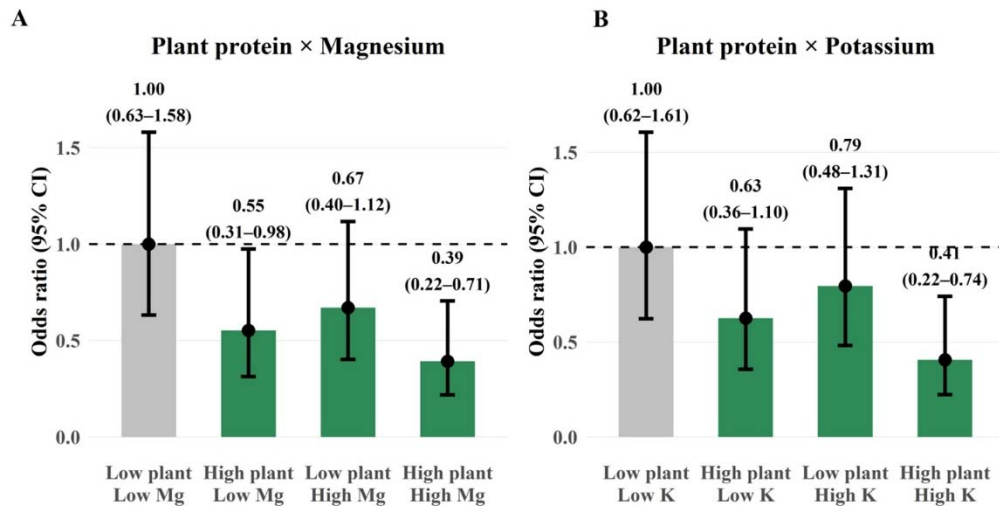


Figure 4. Joint associations of plant protein intake and dietary magnesium or potassium intake with GH risk. Joint categories were created by dichotomizing plant protein and magnesium or potassium intake at their median values, resulting in 4 groups for each joint analysis. Odds ratios (ORs) and 95% confidence intervals (CIs) were estimated using logistic regression. Models were adjusted for the same covariates as in Figure 1. Bars represent ORs, and error bars represent 95% CIs.

Additive interaction analyses, assessed by relative excess risk due to interaction (RERI), attributable proportion (AP), and synergy index (S), did not indicate statistically significant interactions (**Table S6**).

3.7 Sensitive and Stratified analyses

Sensitivity analyses were consistent with primary findings. Additional adjustment for total energy did not change alter results (**Tables S7–S8**). Expressing protein intake as a percentage of total energy produced similar associations (**Figure S2 and S3**).

In stratified analyses, associations between protein intake and GH risk were consistent across subgroups defined by maternal age (<29 vs. ≥29 years), pre-pregnancy BMI (<20.77 vs. ≥20.77 kg/m²), GDM status, family history of hypertension, and dietary fiber (<12.70 vs. ≥12.70 g/d) or cholesterol (<297.17 vs. ≥297.17 mg/d) intake. No significant interactions were detected (all *p* for interaction > 0.05; **Table S9–11**).

4. Discussion

4.1 Main Findings

In this prospective cohort of 2,160 Chinese pregnant women, we observed a U-shaped association between total protein intake during early gestation and the risk of GH. Specifically, total protein intake below 56.61 g/d was associated with lower GH risk, whereas intake above this threshold was linked to increased risk. Higher plant protein intake was inversely associated with GH risk, while higher animal protein, particularly processed red meat, was positively associated. In addition, greater diversity of protein sources was associated with lower GH risk. Joint analyses further suggested that adequate dietary potassium and magnesium intake may strengthen the protective effect of plant protein with GH.

4.2 Interpretation

The observed U-shaped association between total protein intake and GH risk is consistent with evidence from non-pregnant populations reporting nonlinear relationships between protein intake and hypertension. Data from the China Health and Nutrition Survey reported a similar U-shaped pattern, with the lowest hypertension risk at approximately 62 g/day of total protein^[12]. Other prospective cohorts have also reported increased hypertension risk when protein intake exceeds 14–20% of total energy^[31, 32]. Evidence specific to pregnancy remains limited, and our findings provide quantitative and gestational stage-specific reference values.

In contrast, several studies reported null or inverse associations between protein intake and blood pressure. For example, a rural Chinese cohort found no significant relationship between protein intake and hypertension risk among women, likely due to their much lower baseline intake (mean: 40.1 g/d), which falls below the threshold observed in our study^[19]. Similarly, Mehrabani et al. observed an inverse relationship between protein intake and blood pressure^[33], but their use of open-ended questionnaires may have limited data accuracy. A randomized trial also reported no effect of protein supplementation on blood pressure^[34], possibly because baseline intake and threshold effects were not considered.

Dietary intake in the present study was assessed primarily during early pregnancy (median gestational age = 13.7 weeks). The observed nadir of GH risk at approximately 56.61 g/day closely aligns with the Chinese Dietary Reference Intakes for early pregnancy (EAR = 50 g/day; RNI = 55 g/day). Given that protein requirements increase substantially during mid-to-late gestation, our findings should be interpreted as gestational stage-specific rather than as recommendations applicable across the entire pregnancy.

The inverse association between plant protein intake and GH risk aligns with evidence from dietary pattern research on blood pressure regulation. Plant-forward dietary patterns, such as the DASH diet, consistently emphasize plant-based foods to prevent hypertension^[35, 36]. Prospective cohorts and meta-analyses have similarly reported protective associations of plant protein intake with lower blood pressure^[15, 37, 38]. Recent analyses further indicate that greater consumption and diversity of minimally processed plant proteins are associated with reduced hypertension risk^[39]. In our study, protein derived from nuts was associated with a lower risk of GH, consistent with cohort studies reporting inverse associations between nut consumption and incident hypertension^[40]. Potential mechanisms include a higher arginine-to-lysine ratio promoting nitric oxide synthesis, bioactive compounds and fiber exerting antioxidant and anti-inflammatory effects^[41, 42].

By contrast, higher animal protein intake was associated with increased GH risk once intake exceeded threshold levels, consistent with findings from the China Health and Nutrition Survey^[32]. This association was largely driven by processed red meat. Previous studies have reported null associations^[21, 43, 44] may have been limited by differences in dietary assessment or by failure to account for nonlinear exposure–response relationships. Metabolites derived from red and processed meat, such as trimethylamine N-oxide (TMAO), have been implicated in vascular dysfunction, oxidative stress, and arterial stiffness^[45]. In addition, branched-chain and aromatic amino acids may activate proinflammatory pathways, impair nitric oxide

synthesis, and contribute to endothelial dysfunction^[46, 47]. At the same time, meat-derived bioactive peptides may exert antihypertensive effects^[48], suggesting that moderate intake may not be harmful and highlighting the importance of intake level and processing status.

We further observed that the protective association of plant protein with GH was stronger among women with higher dietary potassium and magnesium intake, consistent with evidence that these minerals reduce blood pressure in trials and meta-analyses^[49, 50]. Although potassium and magnesium are commonly co-consumed with plant-based protein foods, the observed effect modification suggests that adequate mineral intake may enhance the favorable association of plant protein with GH risk rather than merely reflect dietary collinearity. Notably, effect modification was observed on the multiplicative scale, whereas additive interaction measures were not statistically significant, indicating that joint effects are more appropriately interpreted on a relative risk scale.

Finally, the inverse association between protein source diversity and GH risk adds a novel dimension to the literature, particularly in pregnancy. Previous studies in non-pregnant populations have linked diverse protein sources with favorable blood pressure trajectories^[32]. A varied protein profile may provide complementary amino acids and micronutrients while reducing excessive reliance on any single protein source, thereby mitigating potential adverse effects.

4.3 Strengths and limitations

This study has several key strengths. Its prospective cohort design and relatively large sample size allowed assessment of early-pregnancy protein intake in relation to subsequent GH risk with clear temporal ordering. Detailed dietary data enabled separate evaluation of total, plant, and animal protein, as well as individual protein sources. The use of restricted cubic spline models identified nonlinear dose–response relationships and intake thresholds, which are directly relevant to nutritional guidance. In addition, examining protein source diversity provides novel evidence in pregnancy and extends findings from non-pregnant populations

Several limitations should also be acknowledged. First, dietary intake and protein diversity were assessed using a validated FFQ reflecting habitual intake over the preceding month. This approach is suitable for ranking usual intake but may misclassify short-term variation, likely attenuating true associations. Second, while dietary mineral intake was examined in stratified and interaction analyses, corresponding biomarkers were not measured, limiting mechanistic interpretation. Third, the exact gestational timing of GH onset was not uniformly recorded, which precluded time-to-event analyses. However, dietary assessment was completed before 20 weeks' gestation, ensuring appropriate temporal ordering between exposure and outcome. Fourth, the predominantly urban study population may limit generalizability, and confirmation in more diverse populations is warranted.

5. Conclusion

During the first half of gestation, both insufficient and excessive total protein intakes were associated with higher risk of gestational hypertension, with an approximate optimal intake of 56.6 g/day. Higher

intake of plant protein and greater diversity of protein sources were inversely associated with GH risk, whereas higher processed red meat protein was associated with increased risk. Adequate dietary potassium and magnesium may further strengthen the protective effect of plant protein. Collectively, these findings highlight that the quantity, source, and diversity of dietary protein are all relevant to GH prevention. Establishing gestational stage-specific, source-conscious protein intake patterns may help inform targeted nutritional guidance during pregnancy and contribute to improved maternal cardiovascular health.

Acknowledgments

The authors are grateful to all participants of the TJBC for their invaluable contributions and sincerely thank the staff members for their dedication and support in data collection and management.

Competing Interests

The authors declare that they have no competing interests.

Funding Statement

This work was supported by the National Natural Science Foundation of China (grant numbers 81773426, 81903313).

Ethics Approval

This study was conducted according to the guidelines of the Declaration of Helsinki. Ethical approval was obtained from the Ethics Review Committee of Tongji Medical College, Huazhong University of Science and Technology (Ethics Committee Number: 2021IEC[S044]).

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request

Reference

- [1] L. Say, D. Chou, A. Gemmill, et al., Global causes of maternal death: a WHO systematic analysis, *Lancet Glob Health*. 2 (2014) e323-333. [https://doi.org/10.1016/s2214-109x\(14\)70227-x](https://doi.org/10.1016/s2214-109x(14)70227-x).
- [2] A. Schuermans, B. Truong, M. Ardissino, et al., Genetic Associations of Circulating Cardiovascular Proteins With Gestational Hypertension and Preeclampsia, *JAMA Cardiol*. 9 (2024) 209-220. <https://doi.org/10.1001/jamacardio.2023.4994>.
- [3] Gestational Hypertension and Preeclampsia: ACOG Practice Bulletin, Number 222, *Obstet Gynecol*. 135 (2020) e237-e260. <https://doi.org/10.1097/aog.0000000000003891>.
- [4] L.A. Magee, P. von Dadelszen, C.M. Bohun, et al., Serious perinatal complications of non-proteinuric hypertension: an international, multicentre, retrospective cohort study, *J Obstet Gynaecol Can*. 25 (2003) 372-382. [https://doi.org/10.1016/s1701-2163\(16\)30579-5](https://doi.org/10.1016/s1701-2163(16)30579-5).
- [5] B.M. Sibai, C.L. Stella, Diagnosis and management of atypical preeclampsia-eclampsia, *Am J Obstet Gynecol*. 200 (2009) 481.e481-487. <https://doi.org/10.1016/j.ajog.2008.07.048>.
- [6] S.G. Bromfield, Q. Ma, A. DeVries, et al., The association between hypertensive disorders during pregnancy and maternal and neonatal outcomes: a retrospective claims analysis, *BMC Pregnancy Childbirth*. 23 (2023) 514. <https://doi.org/10.1186/s12884-023-05818-9>.

- [7] S. Moresi, C. Martino, S. Salvi, et al., Perinatal outcome in gestational hypertension: Which role for developing preeclampsia. A population-based cohort study, *Eur J Obstet Gynecol Reprod Biol.* 251 (2020) 218-222. <https://doi.org/10.1016/j.ejogrb.2020.05.064>.
- [8] V.D. Garovic, W.M. White, L. Vaughan, et al., Incidence and Long-Term Outcomes of Hypertensive Disorders of Pregnancy, *J Am Coll Cardiol.* 75 (2020) 2323-2334. <https://doi.org/10.1016/j.jacc.2020.03.028>.
- [9] Y.X. Wang, M. Arvizu, J.W. Rich-Edwards, et al., Hypertensive Disorders of Pregnancy and Subsequent Risk of Premature Mortality, *J Am Coll Cardiol.* 77 (2021) 1302-1312. <https://doi.org/10.1016/j.jacc.2021.01.018>.
- [10] J. Jin, Safety of Medications Used During Pregnancy, *Jama.* 328 (2022) 486. <https://doi.org/10.1001/jama.2022.8974>.
- [11] S. Kennedy, The role of diet in lowering blood pressure, *Nurs Stand.* 25 (2011) 39-47. <https://doi.org/10.7748/ns2011.08.25.48.39.c8648>.
- [12] J. He, S. Yu, A. Fang, et al., Association between Protein Intake and the Risk of Hypertension among Chinese Men and Women: A Longitudinal Study, *Nutrients.* 14 (2022) <https://doi.org/10.3390/nu14061276>.
- [13] J. Ranganathan, D. Vennard, R. Waite, et al., Global Food Policy Report, International Food Policy Research Institute (IFPRI). (2016),
- [14] J. Stamler, P. Elliott, H. Kesteloot, et al., Inverse relation of dietary protein markers with blood pressure. Findings for 10,020 men and women in the INTERSALT Study. INTERSALT Cooperative Research Group. INTERNational study of SALT and blood pressure, *Circulation.* 94 (1996) 1629-1634. <https://doi.org/10.1161/01.cir.94.7.1629>.
- [15] J.R. Buendia, M.L. Bradlee, M.R. Singer, et al., Diets higher in protein predict lower high blood pressure risk in Framingham Offspring Study adults, *Am J Hypertens.* 28 (2015) 372-379. <https://doi.org/10.1093/ajh/hpu157>.
- [16] I.M. Hajjar, C.E. Grim, V. George, et al., Impact of diet on blood pressure and age-related changes in blood pressure in the US population: analysis of NHANES III, *Arch Intern Med.* 161 (2001) 589-593. <https://doi.org/10.1001/archinte.161.4.589>.
- [17] W. Altorf-van der Kuil, M.F. Engberink, M.M. Vedder, et al., Sources of dietary protein in relation to blood pressure in a general Dutch population, *PLoS One.* 7 (2012) e30582. <https://doi.org/10.1371/journal.pone.0030582>.
- [18] S.M. Tielemans, D. Kromhout, W. Altorf-van der Kuil, et al., Associations of plant and animal protein intake with 5-year changes in blood pressure: the Zutphen Elderly Study, *Nutr Metab Cardiovasc Dis.* 24 (2014) 1228-1233. <https://doi.org/10.1016/j.numecd.2014.05.013>.
- [19] R. Liu, S. Dang, H. Yan, et al., Association between dietary protein intake and the risk of hypertension: a cross-sectional study from rural western China, *Hypertens Res.* 36 (2013) 972-979. <https://doi.org/10.1038/hr.2013.71>.
- [20] H. Boeing, A.M. Amini, J. Haardt, et al., Dietary protein and blood pressure: an umbrella review of systematic reviews and evaluation of the evidence, *Eur J Nutr.* 63 (2024) 1041-1058. <https://doi.org/10.1007/s00394-024-03336-8>.
- [21] E.A. Larson, F. Magkos, H. Ziegenberg, et al., A high protein low glycemic index diet has no adverse effect on blood pressure in pregnant women with overweight or obesity: a secondary data analysis of a randomized clinical trial, *Front Nutr.* 10 (2023) 1289395. <https://doi.org/10.3389/fnut.2023.1289395>.
- [22] J. Øyen, A.L. Brantsæter, L. Secher Myrmed, et al., Maternal intake of dietary protein from plant and animal sources and development of pharmacologically treated hypertension within 10 years after pregnancy, *Eur J Prev Cardiol.* (2025) <https://doi.org/10.1093/eurjpc/zwaf343>.
- [23] R. Zhao, L. Zhou, G. Lei, et al., Dietary Acid Load Is Positively Associated With Risk of Gestational Diabetes Mellitus in a Prospective Cohort of Chinese Pregnant Women, *Front Nutr.* 9 (2022) 892698. <https://doi.org/10.3389/fnut.2022.892698>.
- [24] H. Zhang, X. Qiu, C. Zhong, et al., Reproducibility and relative validity of a semi-quantitative food frequency questionnaire for Chinese pregnant women, *Nutr J.* 14 (2015) 56. <https://doi.org/10.1186/s12937-015-0044-x>.
- [25] Y. Ge, S. Huang, Y. Li, et al., Pregnancy thiamine and riboflavin intake and the risk of gestational diabetes mellitus: A prospective cohort study, *Am J Clin Nutr.* 117 (2023) 426-435. <https://doi.org/10.1016/j.ajcnut.2022.11.014>.
- [26] Y. Yang, G. Wang, X. Pan, China food composition, Peking University Medical Press, Beijing. 42 (2009) 795-799.
- [27] W.C. Willett, G.R. Howe, L.H. Kushi, Adjustment for total energy intake in epidemiologic studies, *Am J Clin Nutr.* 65 (1997) 1220S-1228S; discussion 1229S-1231S. <https://doi.org/10.1093/ajcn/65.4.1220S>.
- [28] [Diagnosis and treatment of hypertension and pre-eclampsia in pregnancy: a clinical practice guideline in China (2020)], *Zhonghua Fu Chan Ke Za Zhi.* 55 (2020) 227-238. <https://doi.org/10.3760/cma.j.cn112141-20200114-00039>.

- [29] M.A. Brown, L.A. Magee, L.C. Kenny, et al., Hypertensive Disorders of Pregnancy: ISSHP Classification, Diagnosis, and Management Recommendations for International Practice, *Hypertension*. 72 (2018) 24-43. <https://doi.org/10.1161/hypertensionaha.117.10803>.
- [30] S.K. Moghadam, Z. Bahadoran, P. Mirmiran, et al., Association between Dietary Acid Load and Insulin Resistance: Tehran Lipid and Glucose Study,
- [31] E. Lee, J. Choi, A. Ahn, et al., Acceptable macronutrient distribution ranges and hypertension, *Clin Exp Hypertens*. 37 (2015) 463-467. <https://doi.org/10.3109/10641963.2015.1013116>.
- [32] C. Zhou, Q. Wu, Z. Ye, et al., Inverse Association Between Variety of Proteins With Appropriate Quantity From Different Food Sources and New-Onset Hypertension, *Hypertension*. 79 (2022) 1017-1027. <https://doi.org/10.1161/hypertensionaha.121.18222>.
- [33] N. Mohammadifard, S. Mehrabani, M. Asemi, et al., Association of Animal and Plant Proteins Intake with Hypertension in Iranian Adult Population: Isfahan Healthy Heart Program, *Advanced Biomedical Research*. 6 (2017) <https://doi.org/10.4103/2277-9175.213877>.
- [34] M.C. Bosland, E. Enk, J. Schmoll, et al., Soy protein supplementation in men following radical prostatectomy: a 2-year randomized, placebo-controlled clinical trial, *The American Journal of Clinical Nutrition*. 113 (2021) 821-831. <https://doi.org/10.1093/ajcn/nqaa390>.
- [35] F.M. Sacks, L.P. Svetkey, W.M. Vollmer, et al., Effects on blood pressure of reduced dietary sodium and the Dietary Approaches to Stop Hypertension (DASH) diet. DASH-Sodium Collaborative Research Group, *N Engl J Med*. 344 (2001) 3-10. <https://doi.org/10.1056/nejm200101043440101>.
- [36] C.D. Filippou, C.P. Tsioufis, C.G. Thomopoulos, et al., Dietary Approaches to Stop Hypertension (DASH) Diet and Blood Pressure Reduction in Adults with and without Hypertension: A Systematic Review and Meta-Analysis of Randomized Controlled Trials, *Adv Nutr*. 11 (2020) 1150-1160. <https://doi.org/10.1093/advances/nmaa041>.
- [37] C.M. Rebholz, E.E. Friedman, L.J. Powers, et al., Dietary Protein Intake and Blood Pressure: A Meta-Analysis of Randomized Controlled Trials, *American Journal of Epidemiology*. 176 (2012) S27-S43. <https://doi.org/10.1093/aje/kws245>.
- [38] H. Lelong, J. Blacher, J. Baudry, et al., Individual and Combined Effects of Dietary Factors on Risk of Incident Hypertension: Prospective Analysis From the NutriNet-Santé Cohort, *Hypertension*. 70 (2017) 712-720. <https://doi.org/10.1161/hypertensionaha.117.09622>.
- [39] J.Y. Tark, R. Li, B. Yu, et al., Dietary Intake of Protein by Food Source and Incident Hypertension Among Diverse US Adults: The MESA Study, *Journal of the American Heart Association*. 14 (2025) e037813. <https://doi.org/10.1161/JAHA.124.037813>.
- [40] L. Djoussé, T. Rudich, J.M. Gaziano, Nut consumption and risk of hypertension in US male physicians, *Clin Nutr*. 28 (2009) 10-14. <https://doi.org/10.1016/j.clnu.2008.08.005>.
- [41] C. Kojima, Amino acid profiles associated with plant-rich protein diets may contribute to lower blood pressure, *Hypertens Res*. 47 (2024) 2964-2966. <https://doi.org/10.1038/s41440-024-01849-7>.
- [42] M. Tucci, M. Marino, D. Martini, et al., Plant-Based Foods and Vascular Function: A Systematic Review of Dietary Intervention Trials in Older Subjects and Hypothesized Mechanisms of Action, *Nutrients*. 14 (2022) 2615. <https://www.mdpi.com/2072-6643/14/13/2615>
- [43] W. Altorf-van der Kuil, M.F. Engberink, J.M. Geleijnse, et al., Sources of dietary protein and risk of hypertension in a general Dutch population, *Br J Nutr*. 108 (2012) 1897-1903. <https://doi.org/10.1017/s0007114512000049>.
- [44] W. Altorf-van der Kuil, M.F. Engberink, F.J. van Rooij, et al., Dietary protein and risk of hypertension in a Dutch older population: the Rotterdam study, *J Hypertens*. 28 (2010) 2394-2400. <https://doi.org/10.1097/HJH.0b013e32833eff63>.
- [45] K.H. Mutengo, S.K. Masenga, A. Mweemba, et al., Gut microbiota dependant trimethylamine N-oxide and hypertension, *Front Physiol*. 14 (2023) 1075641. <https://doi.org/10.3389/fphys.2023.1075641>.
- [46] O. Zhenyukh, E. Civantos, M. Ruiz-Ortega, et al., High concentration of branched-chain amino acids promotes oxidative stress, inflammation and migration of human peripheral blood mononuclear cells via mTORC1 activation, *Free Radic Biol Med*. 104 (2017) 165-177. <https://doi.org/10.1016/j.freeradbiomed.2017.01.009>.
- [47] H. Ichinose, T. Nomura, C. Sumi-Ichinose, Metabolism of tetrahydrobiopterin: its relevance in monoaminergic neurons and neurological disorders, *Chem Rec*. 8 (2008) 378-385. <https://doi.org/10.1002/tcr.20166>.

- [48] M. Martin, A. Deussen, Effects of natural peptides from food proteins on angiotensin converting enzyme activity and hypertension, *Crit Rev Food Sci Nutr.* 59 (2019) 1264-1283. <https://doi.org/10.1080/10408398.2017.1402750>.
- [49] N.J. Aburto, S. Hanson, H. Gutierrez, et al., Effect of increased potassium intake on cardiovascular risk factors and disease: systematic review and meta-analyses, *BMJ : British Medical Journal.* 346 (2013) f1378. <https://doi.org/10.1136/bmj.f1378>.
- [50] X. Zhang, Y. Li, L.C. Del Gobbo, et al., Effects of Magnesium Supplementation on Blood Pressure: A Meta-Analysis of Randomized Double-Blind Placebo-Controlled Trials, *Hypertension.* 68 (2016) 324-333. <https://doi.org/10.1161/hypertensionaha.116.07664>.