Dietary protein intake during pregnancy and birth weight among Chinese pregnant women with low intake of protein

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Abstract

Background: Previous studies have yielded inconsistent results on the association between maternal dietary protein intake and birth weight. Moreover, little is known about the effects of dietary protein intake from different sources on fetal growth. This study aimed to investigate the associations of different dietary protein sources (total protein, animal protein, plant protein, and major dietary protein sources) during pregnancy with birth weight and the related adverse birth outcomes.

Methods: 7310 women were recruited using a stratified multistage random sampling method at 0–12 months (median: 3; 10–90th percentile: 0–7) after delivery in Shaanxi, China. Maternal diets were gathered by a validated FFQ and other characteristics were collected by a standard questionnaire. Multilevel linear or logistic regression models were used to estimate birth weight changes or ORs (95% CIs) for adverse birth outcomes associated with different dietary protein sources during pregnancy.

Results: The mean percentage of energy from total protein was 11.4% (SD 2.2), with only 27.4% of total protein derived from animal protein. Per 3% increase in energy from total protein, animal protein, and dairy protein was associated with birth weight increases of 19.4 g (95% CI 6.0–32.9), 20.6 g (4.8–36.5), and 18.2 g (4.7–31.7), respectively. Per 3% increase in energy from total protein, animal protein, and dairy protein was also associated with lower risks of low birth weight (LBW) (total protein: OR = 0.78, 95% CI 0.64–0.94; animal protein: 0.79, 0.65–0.96; dairy protein: 0.71, 0.56–0.91), small for gestational age (SGA) (total protein: 0.88, 0.79–0.98; animal protein: 0.87, 0.78–0.97; dairy protein: 0.81, 0.68–0.96), and intrauterine growth retardation (IUGR) (total protein: 0.84, 0.72–0.98; animal protein: 0.86, 0.75–0.98; dairy protein: 0.78, 0.66–0.92). We observed no associations of plant protein and other major dietary protein sources with birth weight and the above birth outcomes. The results did not change when maternal protein was substituted for fat or carbohydrate.

Conclusions: Among Chinese pregnant women with low intake of protein, higher intake of dietary protein, in particular animal protein and dairy protein, is associated with higher birth weight and lower risks of LBW, SGA, and IUGR.

Keywords: Birth weight, Fetal growth, Maternal protein intake, Pregnancy
Background

Birth weight is an important indicator for fetal growth. Adverse birth weight, especially the related adverse birth outcomes, such as low birth weight (LBW), small for gestational age (SGA), and intrauterine growth retardation (IUGR), could influence not only perinatal mortality and morbidity but also the cardiometabolic health in adulthood [1]. Some studies have indicated that mother’s excess body weight in pregnancy can influence offspring weight through dietary habits and gut microbiota [2]. However, the underlying mechanisms of fetal growth have not been fully elucidated. Therefore, it is important to identify modifiable risk factors to provide evidence for the primary prevention of adverse birth weight.

Maternal nutrition during pregnancy, as an important modifiable factor, is critical for fetal growth. Among the nutrients studied, protein in particular appears to play a major role for fetal growth. Animal studies have shown that both insufficient and excessive dietary protein intake during pregnancy produced offspring with low birth weight [3]. However, findings from human observational studies on the effect of dietary protein intake during pregnancy on birth weight are inconsistent. Some studies showed a positive association between maternal protein intake and birth weight [4–7], while other studies reported no significant association [8–11], an inverse association [12–14], or even an inverse U-curve association [15]. To our knowledge, evidence on the independent effect of dietary protein intake during pregnancy on birth weight is scare in China, where maternal diets during pregnancy are typically monotonous and predominantly plant-based with little consumption of animal-based foods, especially in Northwest China [16, 17].

The primary sources of dietary protein are animal-based foods and plant-based foods [18]. Previous evidence have suggested that protein actions may vary by the amino acid types and food sources [19, 20]. However, the measurement of dietary protein intake during pregnancy has been mostly limited to total protein intake in the published human studies about birth weight and the related adverse birth outcomes. Only a few studies in Western countries have evaluated the associations of dietary protein intake from different sources during pregnancy with fetal growth [6, 21, 22]. To our knowledge, evidence on the effects of different dietary protein sources during pregnancy on birth weight and the related adverse birth outcomes is scare in Asian countries including China, where dietary habits, lifestyle factors, and fetal growth characteristics differ considerably from those in Western populations.

The present study aimed to explore the associations of different dietary protein sources (total protein, animal protein, plant protein, and major dietary protein sources) during pregnancy with birth weight and the related adverse birth outcomes (LBW, SGA, and IUGR) in Shaanxi Province of Northwest China.

Methods

Study design and participants

Details of the study design have been reported previously [17, 23]. In brief, a population-based cross-sectional study was performed in Shaanxi Province of Northwest China between August and November 2013. This area is normally divided into three regions: northern, southern, and central Shaanxi, with natural resources, culture, and lifestyle differing greatly among them. A total of 30,027 women who were pregnant during 2010–2013 were recruited using a stratified multistage random sampling method. The sampling process is as follows: twenty counties and ten districts were randomly sampled according to the proportion of rural to urban residents, population size, and fertility rate in Shaanxi, China; in each sampled county, six villages each from six townships were randomly selected; in each sampled district, six communities each from three streets were randomly selected; 30 and 60 eligible women were randomly selected from each selected village and community, respectively. Among the participants, 7750 women who were pregnant during 2012–2013 and had infants less than 12 months old were further interviewed to report their diets during pregnancy. We excluded 87 women with a multiple gestation, 65 women without offspring birth weight, and 288 women with an implausible total energy intake (less than 500 kcal/day or greater than 5000 kcal/day), leaving 7310 eligible participants for the final analysis. The flow diagram of sampling strategy with exclusion criteria is shown in Additional file 1: Fig. S1.

This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures were approved by the Xi’an Jiaotong University Health Science Center. Written informed consent was obtained from all participants.

Maternal dietary assessment

Maternal dietary intake during the whole pregnancy was collected by a 107-item semi-quantitative food frequency questionnaire (FFQ) at 0–12 months (median: 3; 10–90th percentiles: 0–7) after delivery [17, 23]. Maternal dietary patterns and nutrient intakes tended to change little from early to late pregnancy [24]; thus, for large-scale epidemiological studies, especially for those with multiple dietary exposures and outcomes like the present study, diet assessment during the whole pregnancy at one time
was reasonable, convenient, and economical [17, 23, 25]. The FFQ was established according to the previously validated FFQ designed for pregnant women in Shaanxi, China [26]. In the validation study, the Pearson correlation coefficient for protein between the FFQ and the average of six 24-h recalls was 0.61, with a range of 0.53 to 0.70 for other nutrients [26]. The frequency scales of five food items (animal oils, vegetable oils, salt, sugar, and sauce) were open-ended, and were listed as kilograms per month and the number of people regularly consuming them. The frequency of the other 102 food items was reported according to eight predefined categories ranging from never to two or more times per day, and their portion sizes were recorded according to food portion images [17, 23]. Daily intakes of total dietary protein, animal protein, plant protein, major dietary protein sources, and other nutrients were transformed using the China Food Composition Tables [27, 28]. Animal protein was derived from animal-based foods, including pork, beef, lamb, chicken and other poultry, eggs, dairy, fish, and seafoods. Plant protein was derived from plant-based foods, including cereals, legumes, nuts, vegetables, and fruits. The recommended percentages of energy from protein, fat, and carbohydrate in China were 10–20%, 20–30%, and 50–65%, respectively [29]. The recommended additional caloric intake per day during the first, second, and third trimesters of pregnancy in China was 0, 300 kcal, and 450 kcal, respectively [29].

Birth outcomes assessment
Neonatal information including birth weight, gestational age, sex, and birth date was obtained by reviewing birth certificates. Birth certificates were finished by the medical staff once the neonates were born. Birth weight was measured with a baby scale with precision to the nearest 10 g. Gestational age at delivery was calculated according to the last menstrual period, and was confirmed by ultrasound scans. Medical history including physical examinations, clinical diagnosis, and medical history were referred to ascertain birth outcomes. The primary outcome of the present study was birth weight, and the secondary outcomes were LBW, SGA, and IUGR. LBW was defined as birth weight <2500 g. SGA was defined as birth weight below 10th percentile of the gestational age-sex specific international reference for fetal growth [30]. IUGR was defined as birth weight below 3rd percentile of the gestational age-sex specific international reference for fetal growth [30].

Covariates assessment
The general information of the participants during pregnancy was collected face to face by well-trained interviewers using a standard questionnaire. The study information was classified as follows: (1) socio-demographic characteristics: geographic area (northern, southern, or central Shaanxi); residence (rural or urban); childbearing age (<25 years, 25–29 years, or ≥30 years); maternal education (primary school or below, junior high school, or senior high school or above); maternal occupation (farmer or working outside); nulliparity (yes or no); (2) health-related characteristics: passive smoking (yes or no); alcohol drinking (yes or no); antenatal care visit frequency (<6 or ≥6); folate/iron supplements use (yes or no); anemia (yes or no); medication use (yes or no). Passive smoking was defined as being exposed to other people’s tobacco smoke for ≥15 min/day. Alcohol drinking included a wide range of alcoholic beverages (liquor, wine, and beer) consumed in pregnancy. Folate/iron supplements use was defined as taking dietary supplements containing folate or iron for more than 2 weeks. Anemia in pregnancy was diagnosed using the criteria of hemoglobin concentration <110 g/L.. Medication use was defined as taking any medication in pregnancy.

Statistical analyses
Because total energy intake is correlated with most nutrients, macronutrient intake was expressed as a percentage of total energy intake by the nutrient-density method and other nutrients were energy-adjusted by the residual method [31]. The study population characteristics according to quartiles of total dietary protein and animal protein intakes were described as percentages or means, with differences tested by χ² test for categorical variables and analysis of variance for continuous variables. Household wealth index was established by principal component analysis according to the items reflecting family economic level (housing condition, vehicle type, income source, and type and number of household appliance), and this index was divided into thirds as an indicator for the poor, medium, and rich households [32]. To avoid multicollinearity of nutrients in regression analyses, we extracted the first component by principal component analysis according to the intakes of potential nutrients (vitamin A, thiamin, riboflavin, folate, vitamin C, vitamin E, calcium, zinc, and selenium) that explained 67.5% of the total variance, with the factor loadings of zinc, riboflavin, folate, thiamin, calcium, and selenium above 0.80.

Considering the stratified multistage random sampling design, multilevel models were applied to assess the associations of dietary protein intake with birth weight and the related adverse birth outcomes (LBW, SGA, and IUGR). After running the four-level empty models representing county (district)-township (community)-village(street)-individual, we observed nonsignificant within-group variations (all P > 0.05) and low intra-class correlations (all lower than 0.001) of the village (street)
level; thus, simplified multilevel models with a random intercept at the county (district) and the township (community) levels were adopted. Multilevel linear regression models were used to estimate birth weight changes associated with different dietary protein sources during pregnancy, and multilevel logistic regression models were used to evaluate ORs (95% CIs) for adverse birth outcomes associated with different dietary protein sources during pregnancy. Protein intake values were computed as 3% energy units to assess the associations. The 3% energy unit was chosen because it was identical around 60 kcal energy and 15 g protein in the study population, which could be easily realized by increasing 75 g pork lean or 60 g chicken breast according to the China Food Composition Tables [27, 28]. Dietary protein intake was also categorized into quartiles to avoid the possible influence of extreme values. Based on previous studies [23, 33], models were adjusted for total energy intake, socio-demographic characteristics (including geographic area, residence, childbearing age, education, occupation, household wealth index, and parity), health-related characteristics (including passive smoking, alcohol drinking, antenatal care visit frequency, folate/iron supplements use, anemia, and medication use), and principal component score based on the nutrient intakes. For birth weight and LBW, models were additionally adjusted for offspring sex and gestational age. Animal protein and plant protein were mutually adjusted for one another. Further adjustment for other major dietary protein sources was performed in the analysis of specific major dietary protein source. To test for a linear trend, we used the median for each quartile of protein intake as a continuous variable. We further evaluated the interactions by introducing cross-product terms into regression models to assess whether the associations were modified by baseline characteristics including offspring sex, geographic area, residence, childbearing age, maternal education, maternal occupation, household wealth index, and parity.

To simulate the substitution of dietary protein for carbohydrate, we fitted isocaloric models [31] by simultaneously including the percentages of energy from fat and protein, total energy intake, and all other potential confounders. The effect estimate from this model can reflect the effect of increasing protein intake at the expense of carbohydrate while keeping calories constant. Similarly, to simulate the substitution of dietary protein for fat, we simultaneously included the percentages of energy from carbohydrate and protein, total energy intake, and all other potential confounders.

A two-tailed P<0.05 was considered as statistically significant. All statistical analyses were performed using STATA software (version 12.0; StataCorp, College Station, Texas, USA).

Results
Baseline characteristics
The baseline characteristics of participants by quartiles of total protein and animal protein intakes are present in Table 1. Participants with higher total protein and animal protein intakes tended to be in northern Shaanxi and southern Shaanxi, respectively. Participants with higher total protein and animal protein intakes were more likely to be urban residents, aged 25–29 years at delivery, better educated, work outside, wealthier, at the first delivery, have more than six antenatal care visits, and take folate/iron supplements, and less likely to be exposed to passive smoking. Total protein intake was positively associated with total energy and most nutrient intakes, and negatively associated with fat, monounsaturated fat, polyunsaturated fat, and vitamin E intakes. Animal protein intake was positively associated with total energy and most nutrient intakes, and negatively associated with plant protein, monounsaturated fat, polyunsaturated fat, carbohydrate, and vitamin E intakes. The offspring birth weight and gestational age were 3263 g (SD 440) and 39.6 weeks (SD 1.3), respectively. The results of univariable comparisons suggested significant differences in birth weight and the prevalence of LBW, SGA, and IUGR among quartiles of total protein and animal protein intakes.

Status of macronutrient intake
The status of macronutrient intake among pregnant women in Shaanxi, China is shown in Table 2. Dietary protein intake per day in the study population during pregnancy was 66.9 g, which was higher than the recommended level in the first trimester in China (55 g), but lower than the recommended level in the second and third trimesters (70 g and 85 g, respectively). The mean percentages of energy from protein, fat, and carbohydrate were 11.4% (SD 2.2), 34.4% (SD 9.8), and 53.5% (SD 10.6), respectively. The percentages of participants having energy from macronutrient in the recommended ranges were 74.4% for protein, 31.2% for fat, and 58.6% for carbohydrate, with only 18.1% participants having energy from all three macronutrients in the recommended ranges. In particular, 25.2% participants had energy from dietary protein lower than the lower limit of the recommended range 10%. Plant protein accounted for the majority of total protein intake (72.5%), of which cereal was the greatest contributor and provided 46.9% of total protein. Animal protein accounted for only 27.4% of total protein, and the main contributors to animal protein were red meat (34.4%), dairy (23.5%), and eggs (19.7%).
Table 1  Baseline characteristics of participants by quartiles of total protein and animal protein intakes (% of energy) among pregnant women in Shaanxi Province, Northwest China

| Total protein intake (% of energy) | Animal protein intake (% of energy) |
|-----------------------------------|-----------------------------------|
| Q1  | Q2  | Q3  | Q4  | P<0.001 | Q1  | Q2  | Q3  | Q4  | P<0.001 |
|------|------|------|------|---------|------|------|------|------|---------|
| Number of participants            | 1827 | 1828 | 1828 | 1827    | 1827 | 1828 | 1828 | 1827    | 1827    |
| General characteristics           |      |      |      |         |      |      |      |         |         |
| Geographic area (%)               |      |      |      |         |      |      |      |         |         |
| Northern Shaanxi                  | 36.0 | 54.8 | 57.5 | 61.0    | 48.6 | 56.9 | 53.8 | 49.9    | 40.4    |
| Southern Shaanxi                  | 43.6 | 25.3 | 22.7 | 24.3    | 25.7 | 22.6 | 28.1 | 39.5    | 31.7    |
| Central Shaanxi                   | 20.4 | 19.9 | 19.8 | 14.7    | 25.7 | 20.5 | 18.1 | 10.6    | 18.9    |
| Rural residence (%)               | 84.2 | 82.4 | 74.8 | 62.9    | 88.0 | 83.7 | 73.6 | 58.8    | 82.5    |
| Childbearing age (%)              |      |      |      |         |      |      |      |         |         |
| < 25 years                        | 47.9 | 43.0 | 39.0 | 36.1    | 43.2 | 43.0 | 41.2 | 38.5    | 42.0    |
| 25–29 years                       | 32.7 | 37.1 | 39.1 | 42.2    | 35.5 | 35.9 | 38.7 | 41.0    | 36.4    |
| ≥ 30 years                        | 19.5 | 20.0 | 21.9 | 21.7    | 21.3 | 21.1 | 20.2 | 20.5    | 21.6    |
| Maternal education (%)            |      |      |      |         |      |      |      |         |         |
| Primary school or below           | 13.3 | 8.2  | 8.1  | 7.0     | 15.6 | 9.0  | 6.2  | 5.8     | 9.0     |
| Junior high school                | 59.9 | 59.7 | 51.4 | 43.3    | 60.7 | 57.9 | 52.9 | 42.6    | 51.7    |
| Senior high school or above       | 26.9 | 32.2 | 41.5 | 49.8    | 23.8 | 33.1 | 40.9 | 51.5    | 39.6    |
| Farmer (%)                        | 78.3 | 74.3 | 70.4 | 62.9    | 80.9 | 74.4 | 69.6 | 61.0    | 71.2    |
| Household wealth index (%)        |      |      |      |         |      |      |      |         |         |
| Poor                              | 30.4 | 33.8 | 30.7 | 27.1    | 32.3 | 34.1 | 31.6 | 24.0    | 31.3    |
| Medium                            | 39.2 | 38.5 | 37.0 | 33.5    | 40.4 | 39.0 | 35.7 | 33.2    | 34.9    |
| Rich                              | 30.3 | 27.7 | 32.3 | 39.4    | 27.3 | 26.9 | 32.7 | 42.9    | 24.7    |
| Nulliparity (%)                   | 58.1 | 58.2 | 58.5 | 64.6    | 50.4 | 58.0 | 62.1 | 68.9    | 59.2    |
| Passive smoking (%)               | 23.8 | 23.3 | 19.9 | 17.8    | 26.2 | 21.7 | 19.3 | 17.6    | 24.7    |
| Alcohol drinking (%)              | 1.6  | 1.2  | 1.1  | 1.3     | 1.3  | 1.0  | 1.4  | 1.7     | 1.25    |
| > 6 antenatal check visits (%)    | 50.4 | 50.1 | 56.1 | 63.5    | 43.1 | 49.4 | 58.3 | 69.3    | 52.6    |
| Folate/iron supplements use (%)   | 88.1 | 89.9 | 92.0 | 92.9    | 86.4 | 90.3 | 92.5 | 94.6    | 86.7    |
| Anemia (%)                        | 19.6 | 18.3 | 18.3 | 17.7    | 18.3 | 20.4 | 17.6 | 17.5    | 18.3    |
| Medication use (%)                | 19.4 | 19.8 | 18.3 | 18.9    | 29.7 | 19.2 | 19.0 | 18.4    | 16.9    |
| Nutrient intake<sup>b</sup>        |      |      |      |         |      |      |      |         |         |
| Total energy (kcal/day)           | 1772.5| 2169.2| 2424.4| 2687.5|<0.001 | 1902.1| 2217.3| 2345.1| 2589.2|<0.001 |
| Protein (% of energy)             | 8.3  | 10.7 | 12.0 | 14.5    | 9.5  | 10.9 | 11.6 | 13.7    | 9.0     |
| Animal protein (% of energy)      | 1.5  | 2.3  | 3.0  | 5.1     | 0.8  | 2.0  | 3.2  | 6.0     | 0.25    |
| Plant protein (% of energy)       | 6.8  | 8.4  | 9.0  | 9.4     | 8.7  | 8.9  | 8.4  | 7.6     | 0.025   |
| Fat (% of energy)                 | 40.0 | 32.3 | 32.0 | 33.3    | 32.9 | 32.1 | 34.7 | 38.0    | 0.001   |
| Saturated fat (% of energy)       | 8.2  | 8.3  | 9.1  | 10.3    | 6.7  | 8.1  | 9.6  | 11.6    | 0.001   |
| Monounsaturated fat (% of energy) | 19.4 | 13.7 | 12.8 | 12.4    | 15.5 | 13.7 | 14.3 | 14.9    | 0.001   |
| Polyunsaturated fat (% of energy) | 9.2  | 7.4  | 7.1  | 7.1     | 8.2  | 7.6  | 7.5  | 7.4     | 0.001   |
| Carbohydrate (% of energy)        | 49.7 | 57.4 | 57.1 | 53.9    | 57.2 | 57.7 | 54.3 | 48.9    | 53.2    |
| Vitamin A (μg retinol equivalent/day) | 362   | 333   | 391   | 723    | 349   | 332   | 383   | 745    | 323    |
| Thiamin (mg/day)                  | 0.6  | 0.7  | 0.7  | 0.8     | 0.6  | 0.7  | 0.7  | 0.7     | 0.6     |
| Riboflavin (mg/day)               | 0.6  | 0.6  | 0.7  | 0.9     | 0.5  | 0.6  | 0.7  | 0.9     | 0.5     |
| Folate (μg/day)                   | 239  | 252  | 291  | 399    | 264  | 277  | 295  | 343    | 271    |
| Vitamin C (mg/day)                | 53   | 57   | 60   | 72     | 57   | 59   | 60   | 62     | 59     |
| Vitamin E (mg/day)                | 46   | 40   | 39   | 39     | 42   | 42   | 42   | 41     | 42     |
| Calcium (mg/day)                  | 483  | 528  | 581  | 676    | 472  | 534  | 592  | 669    | 572    |
| Iron (mg/day)                     | 28   | 29   | 30   | 31     | 28   | 29   | 29   | 30     | 28     |
| Zinc (mg/day)                     | 5.5  | 5.6  | 6.2  | 7.9    | 5.4  | 5.7  | 6.3  | 7.7    | 5.4     |
| Selenium (mg/day)                 | 26   | 27   | 29   | 42     | 25   | 26   | 29   | 44     | 25     |
Associations of total protein, animal protein, and plant protein intakes during pregnancy with birth weight, LBW, SGA, and IUGR

The magnitude of change in birth weight associated with dietary protein intake during pregnancy is displayed in Fig. 1. In the full adjusted models, per 3% increase in energy from total protein and animal protein intakes during pregnancy was associated with birth weight increases of 19.4 g (95% CI 6.0–32.9; \( P = 0.004 \)) and 20.6 g (95% CI 4.8–36.5; \( P = 0.009 \)), respectively. However, we observed no significant increase in birth weight associated with plant protein intake during pregnancy.

The mean intakes of total protein during pregnancy in this population were 8.3% and 14.5% of energy in the lowest and the highest quartiles, respectively. After adjusted for all potential confounders, the risks of LBW, SGA, and IUGR were inversely associated with total protein intake (all \( P \) for trend < 0.05) (Table 3). Compared with the lowest quartile, the adjusted ORs (95% CIs) for the highest quartile of maternal total protein intake were 0.58 (0.36–0.92) for LBW, 0.86 (0.74–0.99) for SGA, and 0.71 (0.54–0.93) for IUGR. Per 3% increase in energy from total protein intake during pregnancy was associated with 22% lower risk of LBW (0.78, 0.64–0.94), 12% lower risk of SGA (0.87, 0.78–0.97), and 16% lower risk of IUGR (0.86, 0.75–0.98).

However, we found no significant associations of plant protein intake during pregnancy with LBW, SGA, and IUGR (Table 3).

### Table 1 (continued)

| Pregnancy outcomes | Total protein intake (% of energy) | Animal protein intake (% of energy) |
|--------------------|-----------------------------------|-----------------------------------|
|                    | Q1 Q2 Q3 Q4 \( P^1 \)             | Q1 Q2 Q3 Q4 \( P^1 \)             |
| Birth weight (g)   | 3227.9 3252.0 3266.6 3308.2 < 0.001 | 3231.7 3262.0 3263.2 3297.9 < 0.001 |
| Gestational age (weeks) | 39.6 39.5 39.6 39.6 0.626 | 39.6 39.6 39.5 39.6 0.361 |
| Sex, male (%)      | 50.2 53.4 55.6 53.8 0.110         | 53.1 51.7 54.6 53.7 0.223         |
| Low birth weight (%) | 4.3 3.8 2.9 2.2 0.002             | 4.8 3.0 2.9 2.6 0.001             |
| Small for gestational age (%) | 10.9 10.7 10.7 8.4 0.040 | 12.8 9.9 9.3 8.2 < 0.001 |
| Intrauterine growth retardation (%) | 5.1 4.5 4.2 3.0 0.012 | 5.6 4.3 3.7 3.3 0.004 |

Values were means or %

\( P \) values for the differences among groups were derived from \( \chi^2 \) tests for categorical variables and analysis of variance for continuous variables

Macronutrient intake was present as a percentage of total energy intake by the nutrient-density method, and other nutrients were energy-adjusted by the residual method

### Table 2 Dietary macronutrient intake among pregnant women in Shaanxi Province, Northwest China

| Dietary intake (g/day) | Dietary intake (% of energy) |
|-----------------------|-----------------------------|
| Mean        | SD  | Mean        | SD  |
| Dietary protein intake | 66.9 | 31.7 | 11.4 | 2.2  |
| Animal protein intake | 18.3 | 7.3  | 3.0  | 1.2  |
| Protein intake from red meats\(^a\) | 6.3  | 2.5  | 1.0  | 0.6  |
| Protein intake from poultry     | 2.1  | 1.1  | 0.3  | 0.1  |
| Protein intake from dairy       | 4.3  | 2.2  | 0.7  | 0.3  |
| Protein intake from eggs         | 3.6  | 1.9  | 0.6  | 0.2  |
| Protein intake from fish and seafoods | 2.1  | 1.1  | 0.3  | 0.2  |
| Plant protein intake           | 48.5 | 21.0 | 8.4  | 1.9  |
| Protein intake from cereals     | 31.4 | 13.6 | 5.5  | 1.7  |
| Protein intake from legumes     | 7.2  | 4.8  | 1.2  | 0.5  |
| Protein intake from nuts         | 3.4  | 2.5  | 0.6  | 0.3  |
| Protein intake from vegetables and fruits | 6.1  | 3.6  | 1.0  | 0.6  |
| Dietary fat intake        | 85.7 | 36.5 | 34.4 | 9.8  |
| Saturated fat intake       | 23.5 | 11.1 | 9.0  | 3.4  |
| Monounsaturated fat intake  | 35.3 | 14.9 | 14.6 | 5.8  |
| Polyunsaturated fat intake  | 18.9 | 8.0  | 7.7  | 2.6  |
| Dietary carbohydrate intake | 311.6 | 121.2 | 53.5 | 10.6 |

\( SD \) standard deviation

\( a \) Red meats included pork, beef, and lamb

**Associations of total protein, animal protein, and plant protein intakes during pregnancy with birth weight, LBW, SGA, and IUGR**

The magnitude of change in birth weight associated with dietary protein intake during pregnancy is displayed in Fig. 1. In the full adjusted models, per 3% increase in energy from total protein and animal protein intakes during pregnancy was associated with birth weight increases of 19.4 g (95% CI 6.0–32.9; \( P = 0.004 \)) and 20.6 g (95% CI 4.8–36.5; \( P = 0.009 \)), respectively. However, we observed no significant increase in birth weight associated with plant protein intake during pregnancy.

The mean intakes of total protein during pregnancy in this population were 8.3% and 14.5% of energy in the lowest and the highest quartiles, respectively. After adjusted for all potential confounders, the risks of LBW, SGA, and IUGR were inversely associated with total protein intake (all \( P \) for trend < 0.05) (Table 3). Compared with the lowest quartile, the adjusted ORs (95% CIs) for the highest quartile of maternal total protein intake were 0.58 (0.36–0.92) for LBW, 0.86 (0.74–0.99) for SGA, and 0.71 (0.54–0.93) for IUGR. Per 3% increase in energy from total protein intake during pregnancy was associated with 22% lower risk of LBW (0.78, 0.64–0.94), 12% lower risk of SGA (0.87, 0.78–0.97), and 16% lower risk of IUGR (0.84, 0.72–0.98). The risks for LBW, SGA, and IUGR were reduced with increasing quartiles of animal protein intake during pregnancy (all \( P \) for trend < 0.05) (Table 3). Compared with the lowest quartile, the adjusted ORs (95% CIs) for the highest quartile of maternal animal protein intake were 0.48 (0.33–0.72) for LBW, 0.76 (0.61–0.95) for SGA, and 0.71 (0.57–0.88) for IUGR. Per 3% increase in energy from animal protein intake during pregnancy was associated with 21% lower risk of LBW (0.79, 0.65–0.96), 13% lower risk of SGA (0.87, 0.78–0.97), and 14% lower risk of IUGR (0.86, 0.75–0.98). However, we found no significant associations of plant protein intake during pregnancy with LBW, SGA, and IUGR (Table 3).
Fig. 1  Birth weight changes associated with per 3% increase in energy from dietary protein intake during pregnancy. Multilevel linear regression models were used to estimate changes and 95% CIs. Model 1 was adjusted for total energy intake, offspring sex, gestational age, and socio-demographic characteristics (including geographic area, residence, childbearing age, education, occupation, household wealth index, and parity). Model 2 was adjusted for all variables in Model 1 plus health-related characteristics (including passive smoking, alcohol drinking, antenatal check visit frequency, folate/iron supplements use, anemia, and medication use) and principal component score based on the nutrient intakes. Models were mutually adjusted for animal protein and plant protein. The black circles represent birth weight changes, and the vertical lines represent 95% CIs.

Table 3  Birth outcomes associated with quartiles of dietary protein intake (% of energy) during pregnancy

|                               | Mean intake ( % of energy) | Low birth weight | Small for gestational age | Intrauterine growth retardation |
|-------------------------------|-----------------------------|------------------|---------------------------|---------------------------------|
|                               | Total protein intake        |                  |                           |                                 |
| Q1                            | 8.3                         | 1                | 1                         | 1                               |
| Q2                            | 10.7                        | 0.85 (0.59, 1.23)| 0.86 (0.59, 1.24)         | 0.98 (0.81, 1.18)               |
| Q3                            | 12.0                        | 0.70 (0.47, 1.05)| 0.72 (0.48, 1.08)         | 0.96 (0.79, 1.17)               |
| Q4                            | 14.5                        | 0.56 (0.35, 0.89)| 0.58 (0.36, 0.92)         | 0.86 (0.75, 0.98)               |
| Per 3% of energy              | 0.77 (0.64, 0.93)           | 0.78 (0.64, 0.94)| 0.87 (0.78, 0.97)         | 0.88 (0.79, 0.98)               |
| P<sub>trend</sub>             | 0.009                       | 0.011            | 0.039                     | 0.046                           |

|                               | Animal protein intake       |                  |                           |                                 |
| Q1                            | 0.8                         | 1                | 1                         | 1                               |
| Q2                            | 2.0                         | 0.58 (0.38, 0.89)| 0.62 (0.41, 0.96)         | 0.79 (0.63, 0.98)               |
| Q3                            | 3.2                         | 0.56 (0.39, 0.82)| 0.59 (0.41, 0.87)         | 0.76 (0.62, 0.93)               |
| Q4                            | 6.0                         | 0.48 (0.33, 0.71)| 0.48 (0.33, 0.72)         | 0.74 (0.58, 0.94)               |
| Per 3% of energy              | 0.78 (0.65, 0.94)           | 0.79 (0.65, 0.96)| 0.86 (0.77, 0.96)         | 0.87 (0.78, 0.97)               |
| P<sub>trend</sub>             | 0.017                       | 0.024            | 0.024                     | 0.029                           |

|                               | Plant protein intake        |                  |                           |                                 |
| Q1                            | 5.9                         | 1                | 1                         | 1                               |
| Q2                            | 8.0                         | 1.03 (0.70, 1.53)| 1.01 (0.68, 1.51)         | 1.06 (0.84, 1.34)               |
| Q3                            | 9.1                         | 0.93 (0.63, 1.36)| 0.94 (0.64, 1.39)         | 1.01 (0.81, 1.27)               |
| Q4                            | 10.7                        | 0.76 (0.49, 1.18)| 0.75 (0.48, 1.17)         | 1.00 (0.78, 1.27)               |
| Per 3% of energy              | 0.87 (0.69, 1.10)           | 0.88 (0.69, 1.11)| 0.95 (0.83, 1.08)         | 0.94 (0.82, 1.08)               |
| P<sub>trend</sub>             | 0.295                       | 0.324            | 0.950                     | 0.941                           |

Multilevel logistic regression models were used to estimate ORs and 95% CIs. Model 1 was adjusted for total energy intake and socio-demographic characteristics (including geographic area, residence, childbearing age, education, occupation, household wealth index, and parity). Model 2 was adjusted for all variables in Model 1 plus health-related characteristics (including passive smoking, alcohol drinking, antenatal check visit frequency, folate/iron supplements use, anemia, and medication use) and principal component score based on the nutrient intakes. Models were mutually adjusted for animal protein and plant protein. Models for low birth weight were additionally adjusted for offspring sex and gestational age.

*P for trend was calculated using the median intake of each quartile as a continuous variable.
Associations of major dietary protein sources during pregnancy with birth weight, LBW, SGA, and IUGR

The magnitude of change in birth weight associated with major dietary protein sources during pregnancy is present in Fig. 2. After adjusted for all potential confounders, per 3% increase in energy from dairy protein intake during pregnancy was associated with an increase of 18.2 g (95% CI 4.7–31.7; \( P = 0.008 \)) in birth weight. The associations of major dietary protein sources during pregnancy with LBW, SGA, and IUGR are shown in Fig. 3. After adjusted for all potential confounders, per 3% increase in energy from dairy protein intake during pregnancy was associated with 29% lower risk of LBW (0.71, 0.56–0.91), 19% lower risk of SGA (0.81, 0.68–0.96), and 22% lower risk of IUGR (0.78, 0.66–0.92). However, there were no significant associations of other major dietary protein sources during pregnancy with birth weight, LBW, SGA, and IUGR.

Roles of modifiable factors

The associations of different dietary protein sources (total protein, animal protein, plant protein, and major dietary protein sources) during pregnancy with birth weight, LBW, SGA, and IUGR were not significantly modified by baseline characteristics including offspring sex, geographic area, residence, childbearing age, maternal education, maternal occupation, household wealth index, and parity (all \( P \) for interaction > 0.05).

Substitution analyses

Substituting 3% energy from carbohydrate with total protein, animal protein, and dairy protein was associated with birth weight increases of 18.9 g (95% CI 4.7–33.2), 20.6 g (95% CI 4.8–36.5), and 19.3 g (95% CI 5.9–32.7), respectively (Additional file 1: Table S1). Substituting 3% energy from carbohydrate with total protein, animal protein, and dairy protein was also associated with lower risks of LBW (total protein: 0.74, 0.59–0.92; animal protein: 0.72, 0.56–0.93; dairy protein: 0.79, 0.63–0.99), SGA (total protein: 0.87, 0.77–0.98; animal protein: 0.86, 0.75–0.98; dairy protein: 0.85, 0.73–0.99), and IUGR (total protein: 0.81, 0.68–0.98; animal protein: 0.84, 0.72–0.98; dairy protein: 0.76, 0.64–0.90) (Additional file 1: Table S1). However, no significant results were observed for the substitution of energy from carbohydrate with plant protein. Similar results were found when energy from protein was exchanged for fat in the associations with birth weight, LBW, SGA, and IUGR (Additional file 1: Table S1).
In our Chinese population with low intake of protein, we observed that higher intake of dietary protein, in particular animal protein, was associated with higher birth weight and lower risks of LBW, SGA, and IUGR. Among specific food sources of protein, higher protein intake from dairy during pregnancy was associated with higher birth weight and lower risks of LBW, SGA, and IUGR. We did not find any significant associations of plant protein and other major dietary protein sources during pregnancy with birth weight, LBW, SGA, and IUGR.

**Comparison with other studies**

Previous human studies on dietary protein intake during pregnancy and fetal growth have generally focused on total protein, and the results were not consistent [4–15]. Similar to the present study, several studies in Spain [4], Australia [5], and the UK [6, 7] showed a positive association between maternal protein intake and birth weight, while other studies found no significant association [8–11], an inverse association [12–14], or even an inverse U-curve association [15]. The inconsistency may be partly due to the differences in study designs, dietary assessment methods, and population characteristics such as dietary habits and genetic backgrounds. In particular, the average percentage of dietary protein intake from energy among Chinese pregnant women in the current study was 11.4%, which was much lower than that among pregnant women in Australia (16.3%) [14], the UK (15.7%) [11], and Malay (15.2%) [9]. According to one survey in rural western China, dietary animal protein intake was 12.1 g for males and 8.3 g for women, and occupied less than 20% of total protein [34]. Which was similar to the low animal protein intake in the present study among pregnant women in Shaanxi, Northwest China. Dietary protein intake per day in our study population during pregnancy was higher than that value reported among women in rural western China (40.1 g) [34], indicating that women in pregnancy tended to improve dietary habits of protein intake. One meta-analysis of randomized controlled trials indicated that providing balanced protein energy supplementation (i.e. supplements in which protein provided less than 25% of total energy) resulted in higher birth weight and lower risk of SGA, especially among undernourished populations [35], which were consistent with our findings in the present study.
studies have evaluated maternal animal and plant protein intakes separately in association with birth weight [6, 21]. One study involving 538 women in the UK reported a positive association between animal protein intake in late pregnancy and birth weight, but no data was presented about plant protein [6]. More recently, another study involving 1698 women in the Netherlands observed a significantly higher birth weight associated with higher intakes of total protein and animal protein, but not plant protein, among those with the BMI of 17.1–21.2 kg/m² at preconception [21], which were consistent with our findings among Chinese population in the current study. Moreover, only a few studies in Western countries have evaluated the association of maternal protein intake from specific food sources with fetal growth [6, 22, 36]. Similar to the current study, previous studies in Denmark [22], the Netherlands [36], and the UK [6] found a positive association between dairy protein intake during pregnancy and birth weight. Dairy protein among Chinese pregnant women in this study was mainly derived from low- and full-fat milk, yogurt, and formula milk. One study in the UK reported a positive association between meat protein intake in late pregnancy and birth weight [6], while this association was not significant in the present study. The discrepancy may be partly explained by the fact that meat protein intake was much lower among Chinese pregnant women than that in the UK (8.4 vs. 28.3 g/day) [6].

Possible mechanisms
Adequate protein intake during pregnancy is crucial to support the synthesis of fetal and placental tissues. However, the biological mechanism by which maternal protein influences fetal growth is unclear. Animal studies have shown that offspring born to protein-restricted mothers had lower insulin-like growth factor concentration [37, 38], which was related with suboptimal fetal growth [39]. Pregnancies complicated by IUGR were reported to be characterized by reductions in both cord plasma amino acid concentrations and placental amino acid transporter activity [40]. The different effects of animal protein and plant protein on fetal growth may be attributable to the difference in amino acid composition. Animal protein can provide all nine indispensable amino acids, while plant protein can be deficient in one or more indispensable proteins such as lysine or threonine. The deficiency in certain indispensable amino acids may repress protein and lipid syntheses through rapamycin (mTOR) pathway [41], which is important for human growth [42]. Dairy protein is a rich source of indispensable amino acids, and may exert more pronounced effects on fetal growth in our population with such low intake of animal protein. The different effects of animal protein and plant protein on fetal growth may also be due to the fact that pregnant women with higher intake of animal protein may have a much better baseline protein status, such that their subsequent increase in animal protein intake may have raised protein levels enough to be beneficial. In fact, participants with a higher intake of animal protein in the current study tended to have better overall nutritional status as shown in Table 2.

Strengths and limitations
To our knowledge, the present study is the first investigation of the associations between dietary protein intake from different sources during pregnancy and fetal growth in Asian countries. This study was conducted in Shaanxi Province of Northwest China using a stratified multi-stage random sampling method, with the large sample size accounting for 3% neonates in Shaanxi, China. The findings of this study could be generalized to other parts of Northwest China according to the similarities in economy, culture, lifestyle, and dietary habits in these regions and could also partly reflect the status in China. Another strength of this study was the relatively accurate birth outcomes obtained by reviewing birth certificates and medical records. However, some limitations merit discussion. First, the dietary and non-dietary information in pregnancy was retrospectively self-reported by the mothers after delivery. Although previous studies suggested that nutrient intakes and events in pregnancy could be recalled rather well even after years [43–45], we cannot rule out the possible misclassification due to recall bias. For example, the FFQ has a tendency of overestimating the food intake. To minimize bias, we have made efforts to help mothers provide accurate responses during the survey. For one thing, we used standard questionnaires and detailed supporting materials such as food portion images and calendars to collect information. For another thing, we conducted a pilot study to test the survey instruments and trained interviewers rigorously according to the detailed guides before the formal survey. Second, we cannot reveal a real causal association because of the cross-sectional design. Third, we cannot fully exclude the possibility of residual confounding from unobserved and unknown factors even after controlling for many potential confounders, including socio-demographic, health-related and dietary factors. For example, we did not gather information on maternal BMI. According to one meta-analysis involving studies in China, low maternal BMI increased the risks of LBW and SGA, and high maternal BMI was associated with fetal overgrowth [46]. Fourth, we did not collect blood samples, and could not further consider the effects of amino acids status and genetic backgrounds on fetal growth.
Conclusions

In conclusion, findings from the current study suggest that, among Chinese pregnant women with low intake of protein, higher intake of dietary protein, in particular animal protein and dairy protein, is associated with higher birth weight and lower risks of LBW, SGA, and IUGR. Large-scale prospective cohort studies are needed to evaluate the effects of amino acids or protein from specific sources on fetal growth in broader populations. Future studies with information on body amino acids or protein status and genetic backgrounds are also warranted to further investigate their associations and to identify underlying mechanisms.

Abbreviations
LBW: Low birth weight; SGA: Small for gestational age; IUGR: Intrauterine growth retardation; FFQ: Food frequency questionnaire.

Supplementary Information
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Additional file 1: Fig. S1. Flow diagram of sampling strategy with exclusion criteria. Table S1. Birth weight and the related adverse birth outcomes associated with isocaloric substitution of 3% energy from dietary protein intake during pregnancy.

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Author contributions
JY, SD, and HY contributed to study concept and design. JY and YL drafted the initial manuscript. JY, QC, XT, BZ, LZ, and YL conducted statistical analyses. JY, QC, BZ, LZ, and SD collected the data. SD, HY and YL revised the manuscript. All authors have read and approved the final version of the manuscript.

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Availability of data and materials
The datasets analysed during the current study are available from the corresponding author on reasonable request.

Declarations
Ethics approval and consent to participate
This study was approved by the Xi’an Jiaotong University Health Science Center. Written informed consent was obtained from all participants.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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References
1. Hoffman DJ, Powell TL, Barrett ES, Hardy DB. Developmental origins of metabolic disease. Physiol Rev. 2021;101:739–95.
2. Paly O, Pyathilake CJ, Kojysykk A, Ceple G, Marotta F, Rastmanesh R. Excess body weight during pregnancy and offspring obesity: potential mechanisms. Nutrition. 2014;30:245–51.
3. Metges CC. Does dietary protein in early life affect the development of adiposity in mammals? J Nutr. 2001;131:2062–6.
4. Guo G, Anja V, Iranzo R, Vila J, Prieto MT, Fernandez-Ballart J. Association of maternal protein intake before conception and throughout pregnancy with birth weight. Acta Obstet Gynecol Scand. 2006;85:413–21.
5. Moore VM, Davies MJ, Willson KJ, Worsley A, Robinson JS. Dietary composition of pregnant women is related to size of the baby at birth. J Nutr. 2004;134:1820–6.
6. Godfrey K, Robinson S, Barker DJ, Osmond C, Cox V. Maternal nutrition in early and late pregnancy in relation to placental and fetal growth. BMJ. 1996;312:410–4.
7. Harte FM, Brooke OG, Anderson HR, Bland JM. The effect of nutritional intake on outcome of pregnancy in smokers and non-smokers. Br J Nutr. 1991;65:347–54.
8. Halldorsson TI, Birgisdottir BE, Brantsaeter AL, Melzter HM, Haugen M, Thorsdottir I, Olafsdottir AS, Olsen SF. Old question revisited: are high-protein diets safe in pregnancy? Nutrients. 2021;13:440.
9. Chong MF, Chia AR, Colega M, Tint MT, Aris IM, Chong YS, Gluckman P, Godfrey KM, Kwek K, Saw SM, et al. Maternal protein intake during pregnancy is not associated with offspring birth weight in a multiethnic asian population. J Nutr. 2015;145:1303–10.
10. Lagiou P, Tamimi RM, Mucci LA, Adami H, Hauec CB, Trichopoulos D. Diet during pregnancy in relation to maternal weight gain and birth size. Eur J Clin Nutr. 2004;58:231–7.
11. Mathews F, Yudkin P, Neil A. Influence of maternal nutrition on outcome of pregnancy: prospective cohort study. BMJ. 1999;319:339–43.
12. Estah ES, Okada C, Baba S, Kimura T, Ikehara S, Sato T, Shirai K, Iso H. Maternal total energy, macronutrient and vitamin intakes during pregnancy associated with the offspring’s birth size in the Japan Environment and Children’s Study. Br J Nutr. 2020;124:558–66.
13. Switkowski KM, Jacques PF, Must A, Kleinman KP, Gillman MW, Oken E. Maternal protein intake during pregnancy and linear growth in the offspring. Am J Clin Nutr. 2016;104:1128–36.
14. Andreasyan K, Ponsonby AL, Dwyer T, Morley R, Riley M, Dear K, Cochrane J. Higher maternal dietary protein intake in late pregnancy is associated with a lower infant ponderal index at birth. Eur J Clin Nutr. 2007;61:498–508.
15. Morisaki N, Nagata C, Yasuo S, Morokuma S, Kato K, Sanefuji M, Shibata E, Tsumi M, Senju A, Kawamoto T, et al. Optimal protein intake during pregnancy for reducing the risk of fetal growth restriction: the Japan Environment and Children’s Study. Br J Nutr. 2018;120:1432–40.
16. Yang J, Cheng Y, Zeng L, Dang S, Yan H. Maternal dietary diversity during pregnancy and congenital heart defects: a case-control study. Eur J Clin Nutr. 2021;75:355–63.
17. Yang J, Dang S, Cheng Y, Qiu H, Mi B, Jiang Y, Qu P, Zeng L, Wang Q, Li Q, et al. Dietary intakes and dietary patterns among pregnant women in Northwest China. Public Health Nutr. 2017;20:282–93.
18. Mousa A, Naqash A, Lim S. Macronutrient and micronutrient intake during pregnancy: an overview of recent evidence. Nutrients. 2019;11:443.
19. Sun Y, Liu B, Sneteslaar LG, Wallace RB, Shadyab AH, Kroenke CH, Haring B, Howard BV, Shikany JM, Valdiviezo C, et al. Association of major dietary protein sources with all-cause and cause-specific mortality: prospective cohort study. J Am Heart Assoc. 2021;10:e015553.

20. Budhathoki S, Sawada N, Iwakoshi M, Yamaji T, Goto A, Kotomori A, Ishihara J, Takuchi R, Charvat H, Mizoue T, et al. Association of animal and plant protein intake with all-cause and cause-specific mortality in a Japanese cohort. JAMA Intern Med. 2019;179:1509–18.

21. Salavati N, Bakker MK, Lewis F, Vanke PC, Mubark F, Erwich JHM, van der Beek EW. Associations between preconception macronutrient intake and birth weight across strata of maternal BMI. PLoS ONE. 2020;15:e0245200.

22. Olsen SF, Hallransson TI, Willcott WC, Knudsen VK, Gillman MW, Mikkelsen TB, Olsen J. Milk consumption during pregnancy is associated with increased infant size at birth: prospective cohort study. Am J Clin Nutr. 2007;86:1104–10.

23. Yang J, Cheng Y, Pei L, Jiang Y, Lei F, Zeng L, Wang Q, Li Q, Kang Y, Shen Y, et al. Maternal iron intake during pregnancy and birth outcomes: a cross-sectional study in Northwest China. Br J Nutr. 2017;117:862–71.

24. Czorier SR, Robinson SM, Godfrey KM, Cooper C, Insipk HM. Women's dietary patterns change little from before to during pregnancy. J Nutr. 2009;139:1956–63.

25. Rifas-Shiman SL, Rich-Edwards JW, Willcott WC, Kleinman KP, Oken E, Gillman MW. Changes in dietary intake from the first to the second trimester of pregnancy. Paediatr Perinat Epidemiol. 2006;20:35–42.

26. Cheng Y, Yan H, Dibley MJ, Shen Y, Li Q, Zeng L. Validity and reproducibility of a semi-quantitative food frequency questionnaire for use among pregnant women in rural China. Asia Pac J Clin Nutr. 2008;17:166–77.

27. Institute of Nutrition and Food Safety CCfDCaP. China food composition book 1. 2nd ed. Beijing: Peking University Medical Press; 2009.

28. Institute of Nutrition and Food Safety, China CDC. China food composition book 2. Beijing: Peking University Medical Press; 2005.

29. Chinese Nutrition Society. Chinese dietary guideline. Beijing: People’s Medical Publishing House; 2016.

30. Villar J, Cheikh Ismail L, Victoria CG, Ohuma EO, Bertino E, Altman DG, Lambert A, Papageorgiou AT, Carvalho M, Jaffer YA, et al. International standards for newborn weight, length, and head circumference by gestational age and sex: the Newborn Cross-Sectional Study of the INTERGROWTH-21st Project. Lancet. 2014;384:857–68.

31. Willcott WC, Howe GR, Kushli LH. Adjustment for total energy intake in epidemiologic studies. Am J Clin Nutr. 1997;65:1205-S1218.

32. Filmer D, Pritchett L. Estimating wealth effects without expenditure data—or tears: an application to educational enrollments in states of India. Demography. 2001;38:115–32.

33. Liu D, Cheng Y, Mi B, Zeng L, Xu P, Li S, Zhang R, Qi Q, Wu C, Gao X, et al. Maternal dietary patterns during pregnancy derived by reduced-rank regression and birth weight in the Chinese population. Br J Nutr. 2017;117:862–71.

34. Liu R, Dang S, Yan H, Wang D, Zhao Y, Li Q, Liu X. Association between dietary protein intake and the risk of hypertension: a cross-sectional study from rural western China. Hypertens Res. 2013;36:972–9.

35. Ota E, Hori H, Mori R, Tohe-Gai R, Farrar D. Antenatal dietary education and supplementation to increase energy and protein intake. Cochrane Database Syst Rev. 2015;6:CD000032.

36. Happe DH, van Dam RM, Willemsen SP, den Breeijen H, Raat H, Hofman A, Steegers EA, Jaddoe WV. Maternal milk consumption, fetal growth, and the risks of neonatal complications: the Generation R Study. Am J Clin Nutr. 2011;94:501–9.

37. El-Khattabi I, Grégoire F, Remacle C, Reusens B. Isoacolamic maternal low-protein diet alters IGF-I, IGFBPs, and hepatocyte proliferation in the fetal rat. Am J Physiol Endocrinol Metab. 2003;285:E991–1000.

38. Petrik J, Reusens B, Arany E, Remacle C, Coelho C, Hoet JJ, Hill DJ. A low protein diet alters the balance of islet cell replication and apoptosis in the fetal and neonatal rat and is associated with a reduced pancreatic expression of insulin-like growth factor-II. Endocrinology. 1999;140:4861–73.

39. Murphy VE, Smith R, Giles WB, Clifton VL. Endocrine regulation of human fetal growth: the role of the mother, placenta, and fetus. Endocr Rev. 2006;27:141–69.

40. Plegnaud TR, de Vrijer B, Battaglia FC. Transport and metabolism of amino acids in placenta. Endocrine. 2002;19:23–41.

41. Clark DC. Association of dairy protein intake during pregnancy with birth weight. Food Nutr Bull. 2018;39:534–9.