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Low selenium intake is associated with postpartum weight retention in Chinese women and impaired physical development of their offspring

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Abstract

The aim of this study was to investigate the association between daily Se intake and postpartum weight retention (PPWR) among Chinese lactating women, and the impact of their Se nutritional status on infants' physical development. Se contents in breast milk and plasma collected from 264 lactating Chinese women at the 42nd day postpartum were analysed with inductively coupled plasma MS. Daily Se intake was calculated based on plasma Se concentration. The dietary data of 24-h records on three consecutive days were collected. Infant growth status was evaluated with WHO standards by *Z*-scores. Linear regression analyses and multinomial logistic regression were conducted to examine the impact of Se disequilibrium (including other factors) on PPWR and growth of infants, respectively. The results indicated that: (1) the daily Se intake of the subjects was negatively associated with their PPWR ($B = -0{\cdot}002$, 95 % CI − 0·003, 0·000, $P = 0{\cdot}039$); (2) both insufficient Se daily intake ($B = -0{\cdot}001$, OR 0·999, 95 % CI 0·998, 1·000, $P = 0{\cdot}014$) and low level of Se in milk ($B = -0{\cdot}025$, OR 0·975, 95 % CI 0·951, 0·999, $P = 0{\cdot}021$) had potential associations with their infants' wasting, and low level of Se in milk ($B = -0{\cdot}159$, OR 0·853, 95 % CI 0·743, 0·980, $P = 0{\cdot}024$) had a significant association with their infants' overweight. In conclusion, the insufficient Se nutritional status of lactating Chinese women was first found as one possible influencing factor of their PPWR as well as low physical development of their offspring.

Key words: **Selenium: Postpartum weight retention: Gestational weight gain: Lactating women: Offspring: *Z*-scores**

Women of reproductive age are especially at risk of developing or worsening obesity, caused by excessive weight gain during pregnancy[1]. Postpartum weight retention (PPWR) is a short- and long-term risk factor for overweight and obesity in women[2,3]. Additionally, PPWR incurs an increased risk for complications in subsequent pregnancies[4,5]. In China, the prevalence of high PPWR at 2 years postpartum was 41·5 % in 2013 (high PPWR was defined as ≥5 kg)[6]. PPWR may be particularly harmful, as its damaging effects cross generations. Recent studies reported that PPWR may be associated with the incidence of diabetes, heart disease and hypertension[7,8]. Moreover, it contributes to an increased risk of obesity in the offspring, causing an intergenerational cycle of obesity[9].

Learning about potential determinants of PPWR is critical for the development of effective interventions to optimise the trajectory of weight gain, particularly among those mothers at high risk. At first, there are many previous researches on the relationships between prepregnancy BMI on either PPWR or offspring weight, which indicated conflicting results[10,13]. Then, many studies have found that the main reason for PPWR was gestational weight gain (GWG)[14,18]. Some studies have indicated that dietary intake is associated with PPWR. A previous cross-sectional survey among lactating women in south central China suggested that pattern with a high intake of fresh vegetables (non-leafy), soya milk, probiotics and algae, and fresh

Abbreviations: GWG, gestational weight gain; LAZ, *Z*-score of length-for-age; PPWR, postpartum weight retention; WAZ, *Z*-score of weight-for-age; WLZ, *Z*-score of weight-for-length.

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legumes was negatively associated with PPWR[19]. Higher energy, protein, carbohydrate and fat intake in diet were significantly associated with higher 6 months PPWR[20]. Also, lactation is a critical period for nutritional needs. A representative traditional Chinese postpartum diet (also called a confinement diet or a diet for puerperium rest and recovery in China, which consists of too much animal foods such as eggs and various soups of chicken or trotters) has an excessive amount of protein and energy which potentially increases the risk for postpartum weight gain over the short-term, obesity and related health problems in the long-term[21,23]. Nutritional requirements increase not only to support infant growth and development but also to promote maternal postpartum recovery[24,25]. Intake of nutrients during this critical period may have an important effect on maternal weight[14].

As suggested from some previous survey, there is marked association of Se nutritional status with human body weight. Some studies founded that blood/serum Se showed positive relationships with obesity or BMI in children, adolescent and adults from all over the world, including China[26,30]. Among them, an intervention study showed that Se supplementation can significantly reduce the body fat mass. A cross-sectional study supported an inverse association between fingernail Se levels and the risk of obesity in Chinese children[31]. Another cross-sectional study also indicated a trend of low Se biomarkers in the overweight/obese group, although the differences were not statistically significant ($P > 0{\cdot}05$)[32]. In addition to functions of immune, endocrine, cardiovascular, reproductive, nervous systems and anti-cancer activity, it is well known that Se plays a significant and dimness role in modulating insulin signalling, and consequently carbohydrate and lipid metabolism[33–40]. During recent decades, some epidemiological surveys around the world also showed that indicators of diabetes or the metabolic syndrome were positively associated with Se content in plasma or nails, as well as selenoprotein P in plasma[41,46]. However, to our known, no survey for this relationship for lactating women was reported.

In consideration of the potential roles of selenoproteins in thyroid function which are critical for body growth and energy production, a cohort study evaluated the association of low Se status with hypothyroidism during pregnancy and the association of maternal low thyroid function with infant birth size, which indicated that low Se status during pregnancy may associate with low thyroid function that was related to low birth weights[47–50]. A prospective observational study in 2014 that involved 126 pregnant women between 28 and 32 weeks gestation revealed an association between lower maternal Se levels and delivery of small-for-gestational age infants suggesting Se deficiency as a possible risk factor for intra-uterine growth retardation[51].

The purpose of this study was to investigate the association between daily Se intake with PPWR among Chinese lactating women, and their infants' physical development.

Methods

Study population

This cross-sectional study recruited 450 lactating mothers from three geographical locations with different Se levels in soil, a Se-deficient area (Liangshan, Sichuan province), a Se-sufficient city (Xicheng District, Beijing) and a Se-toxic region (Enshi, Hubei province), during the first week after delivery in 2014. All participants had delivered a normal single infant at full term and intended to breastfeed their child. As their own cultures and collection of precious breast milk, some subjects did not go back to local hospital again postpartum, especially from these minority areas (Enshi and Liangshan). The eligibility criteria included subjects whose infants were breastfed fully at the end of the third month postpartum, healthy according to self-evaluation and no smoking. Exclusion criteria included women with the metabolic syndrome or chronic diseases, such as diabetes mellitus, hypertension or goitre during pregnancy and lactation. We excluded individuals who have extreme energy intakes: <2093 or >14 650 kJ/d), as identified by the Goldberg equation modified by Black[52]. Thereby, 264 healthy lactating women were included in this study, thirty-seven from Liangshan, 128 from Beijing and ninety-nine from Enshi, which was acceptable for the requirement of >80 % power, regarding Cohen's d criteria (power = 0·80, 95 % CI, $\alpha = 0{\cdot}05$, and $dz = 0{\cdot}50$), based on the Se levels in serum and human milk. All 264 pairs of healthy mothers and their infants were divided into three groups according to daily Se intake. The flow chart of participants is shown in Fig. 1. Written informed consent was obtained from all subjects prior to study participation. This study was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures were approved by the Ethics Committee of National Institute for Nutrition and Health, Chinese Center for Disease Control and Prevention. This study design and examination procedures have been described in detail elsewhere[53].

Demographic information collection

Information on socio-demographic factors including each mother's age, infant's sex, delivery mode (vaginal delivery, forceps delivery or caesarean delivery), parity, exercising and sleeping time were collected by questionnaires.

Dietary assessment

Dietary information was collected using a 24-h food record method on three consecutive days at the 42nd day postpartum. Participants were trained to record meals and snacks consumed by themselves during a 24-h period, for three consecutive days. The weight and volume of each food or beverage were estimated with different sizes of household measuring tools such as bowls, cups and spoons; besides, pictures of each food in the raw and cooked state with reference objects to assure the data were as reliable as possible.

Since this investigation in these participants was conducted in 2014, the daily dietary intakes of energy and three macronutrients were calculated based on the new version of the China Food Composition Tables[54].

Anthropometric measurements

Prepregnancy weight, weight before delivery and current body weight were recorded in kg. The prepregnancy weight, weight before delivery, newborn weights and lengths were obtained

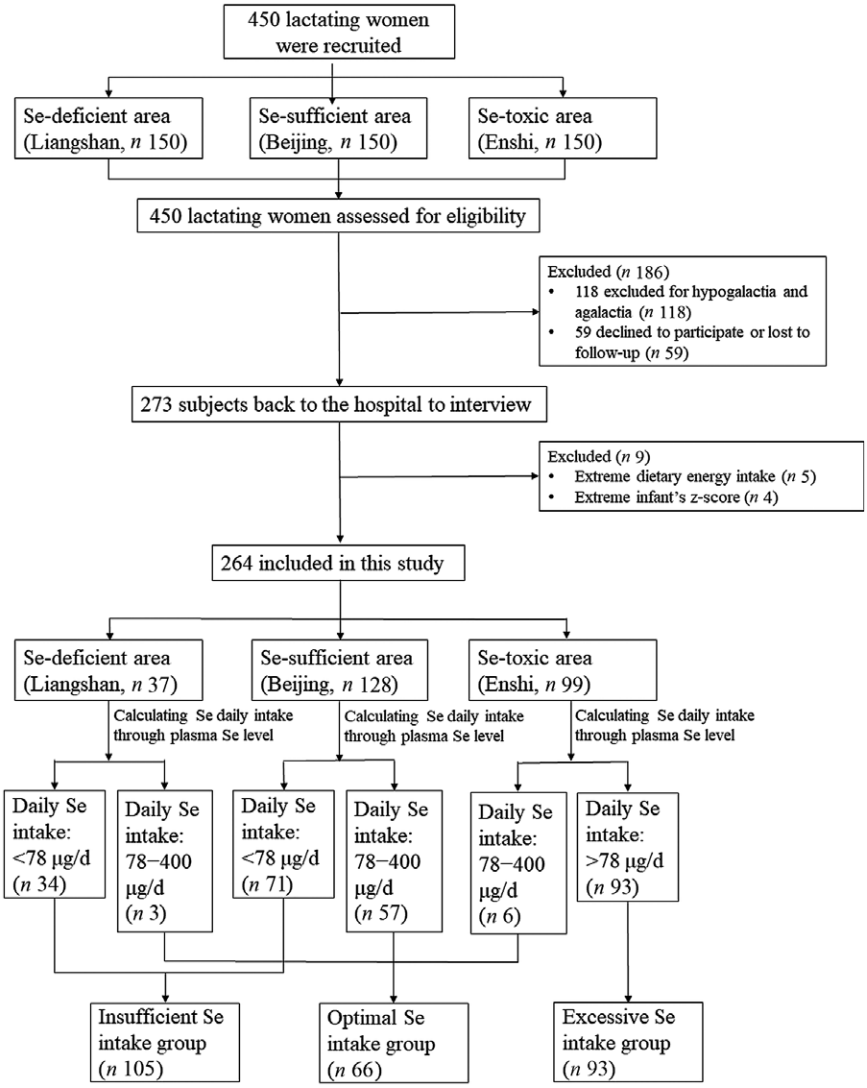

Fig. 1. Flow chart of participants.

from the mothers' Maternal-Infant Health Handbooks. The pre-pregnancy weight was self-reported by each subject. At the 42nd day postpartum, the current maternal weight (to the nearest 100 g) was measured with an electronic scale (TANITA HD370) and height (to the nearest 0·5 cm) was measured by a trained data collector using a measuring tape. The weight (to the nearest 10 g, Seca 335 in Poitiers) and length (to the nearest 0·1 cm, YSC-2 measuring machine) of their infants were also measured. All results were recorded as a mean value, which was calculated from two separate measurements. In the case when a third measurement was taken, a median was used in place of the mean when the difference between the two former measurements was more than 10 %[53]. GWG was calculated as the weight before delivery minus the prepregnancy weight. PPWR was calculated as the current body weight minus the pre-pregnancy weight. According to Institute of Medicine guidelines, prepregnancy BMI was categorised as underweight, normal, overweight or obese and GWG was categorised as insufficient, optimal or excess weight gain (Appendix 1)[55].

Infant physical evaluation

We used the WHO Anthro software to calculate the *Z*-scores of weight-for-length (WLZ), length-for-age (LAZ), weight-for-age (WAZ) according to infant's sex, birth date and check-up date. Based on the WHO growth standards, stunting was defined as LAZ < −2; underweight was defined as WAZ < −2; wasting was defined as weight lighter than the corresponding weight of WLZ of −2 for particular length and sex; overweight means as weight heavier than the corresponding weight of WLZ of 2 for specific length and sex and defined WAZ > 2; obesity was defined as weight heavier than the corresponding weight of WLZ of 3 for particular length and sex[56]. Outliers in outcomes based on the WHO standards (LAZ < −6, LAZ > 6, WAZ < −6, WAZ > 5, WLZ < −5 and WLZ > 5) were also dropped (*n* 4)[56].

Sample collection

At the 42nd day postpartum interview, a 10 ml sample of breast milk and a 5 ml blood sample (collected in a heparin sodium tube

for plasma) were collected from all the subjects. All the above steps were performed by local hospital nurses. To minimise discomfort and maximise participation, mothers could collect breast milk at any time and no time constraints were given for when to express it with respect to their infant's feeding. Blood (3 ml) was centrifuged at 10 000 ***g*** at 4 °C for 10 min to separate the plasma. The samples of milk and plasma were stored at −80°C until chemical analysis was performed[53].

Laboratory analysis

Samples of plasma and breast milk collected at the 42nd day postpartum interview were used for the determination of the Se contents, the procedure of which has been described in details previously[53]. To be specific, a previously heated (25°C) and shaken plasma sample or breast milk sample was digested by a CEM MARS Xpress microwave system (CEM). The cooled, digested samples were diluted to 10 ml with ultrapure water and analysed for total Se content by inductively coupled plasma MS (Agilent 8800). Three independent replicates were conducted, and the respective blanks were considered in the final results. Accuracy of the Se analysis was assessed during each batch of analysis using a standard reference material (SRM 1549, National Institute of Standards and Technology).

The method for the calculation of dietary Se daily intake has also been previously described in details[53]. In brief, as lacking the sufficient data for Se content in each region, the dietary Se intakes were estimated from the plasma Se concentrations by employing the following formula: log (daily Se intake (μg/d)) = 1·623 log (plasma Se concentration (mg/l)) + 3·433[57].

Based on the recommended dietary Se intake for lactating Chinese women[58], 264 early lactating Chinese women were classified into three groups: the insufficient Se group (<78 μg Se/d), the optimal Se group (78–400 μg Se/d) and the excessive Se group (>400 μg Se/d).

Statistical analysis

Epidata software 3.1 was applied to build a database. Means and standard deviations were used to express the values of normally distributed data and medians and 25th and 75th percentiles to express skewed data. The comparison between group differences after ANOVA was evaluated by least significant difference, and when indicated for non-parametric analysis, we used the Mann–Whitney *U* or Kruskal–Wallis test, and χ^2 test for categorical variables. The group changes of infants' *Z*-scores between at birth and at the 42nd day were evaluated by the paired-samples *t* test.

The directed acyclic graph (Fig. 2) used to select the variables was created using DAGitty version 3.0[59]. Multivariable linear regression was conducted to examine the relationships between dietary intake of Se and PPWR, adjusting the following covariates: age, parity, GWG, prepregnancy BMI, dietary intakes of protein fat, carbohydrate and total energy and time of physical activity and sleep, based on Fig. 2(a). Multinomial logistic regression was applied to estimate the associations of change of mothers' weight with their infants' physical *Z*-scores at birth (adjusting for age, parity and household income) and maternal Se nutritional status (including daily Se intake and Se content in human milk) with their infants' *Z*-scores at 42nd day (adjusting for age, parity, *Z*-scores at birth, daily dietary intake of total energy and three macronutrients and household income), based on Fig. 2(b). The dependent variables were the categories of WLZ, LAZ and WAZ, according to WHO growth standards[49].

All of the analyses were performed using SPSS version 25.0 (IBM Corp.). G-Power (version 3.1.9) was used for power analysis. Statistical significance was accepted at a two-sided *P* value of <0·05. The variance inflation factor was used for identifying multicollinearity. No multicollinearity was observed in our multivariate analysis (variance inflation factor < 2·0).

Results

Table 1 shows the demographic characteristics of the lactating women grouped by three different levels of daily Se intake. The lactating women had a mean age of 27 years, and most of these women delivered first time (72·73 %).

The weight characteristics of mothers are presented in Table 2. No significant difference of prepregnancy BMI was observed ($P = 0·706$). GWG in the insufficient Se group and the optimal Se group (15·59 (SD 5·43) and 17·08 (SD 6·72) kg, respectively) were significantly higher than those in the excessive Se group (12·87 (SD 6·63) kg; $P < 0·01$), and the same in PPWR (8·17 (SD 6·17) and 7·86 (SD 6·25) kg *v.* 4·49 (SD 6·02) kg; $P < 0·01$).

Dividing all subjects into four subgroups by the quartiles of the PPWR, significant differences for GWG, prepregnancy BMI and dietary intakes of energy, protein and Se were investigated among women with different quartiles of PPWR ($P = 0·000$, 0·000, 0·004, 0·005 and 0·001, respectively, shown in Table 3). On the basis of the directed acyclic graph (Fig. 2(a)) and our univariate analysis (Table 3), multivariable linear regression analyses were conducted to examine the relationships between dietary daily Se intake and PPWR, adjusting for other potential confounders, including GWG, prepregnancy BMI, dietary intakes of protein, age, parity, dietary intakes of fat, carbohydrate and total energy and time of physical activity and sleep. The association of dietary daily intake Se with PPWR are listed in Table 4. The linear regression model after adjusting indicated that PPWR significantly decreased with dietary intake of Se ($P < 0·05$). The distribution curves of *Z*-scores at two different time points (at birth and 42nd day) for infants of all participants are shown in Appendix 2. The infants were also divided into the same three groups, followed by their mothers. Table 5 presents the WAZ, LAZ and WLZ of infants at different time points (at birth and 42nd day). At birth, most of all have optimal WLZ (89·39 %), LAZ (98·10 %) and WAZ (96·59 %). Compared with infants of lactating women in excessive Se group, infants in other two groups had higher LAZ and WAZ ($P < 0·05$). No significant difference of WLZ was observed in infants among three groups. At 42nd day, infants of mothers in the optimal Se group have the lowest WLZ and highest LAZ ($P < 0·05$). For WAZ, there was no significant difference observed in infants among three groups. Overall, the WAZ of infants increased significantly ($P = 0·002$) during the first 42-d period, especially in excessive Se group ($P < 0·01$) which had a significantly increased WLZ and WAZ ($P = 0·000$) as well as decreased LAZ ($P = 0·000$). In optimal Se intake group, WLZ of infants markedly decreased ($P = 0·002$), while LAZ significantly increased

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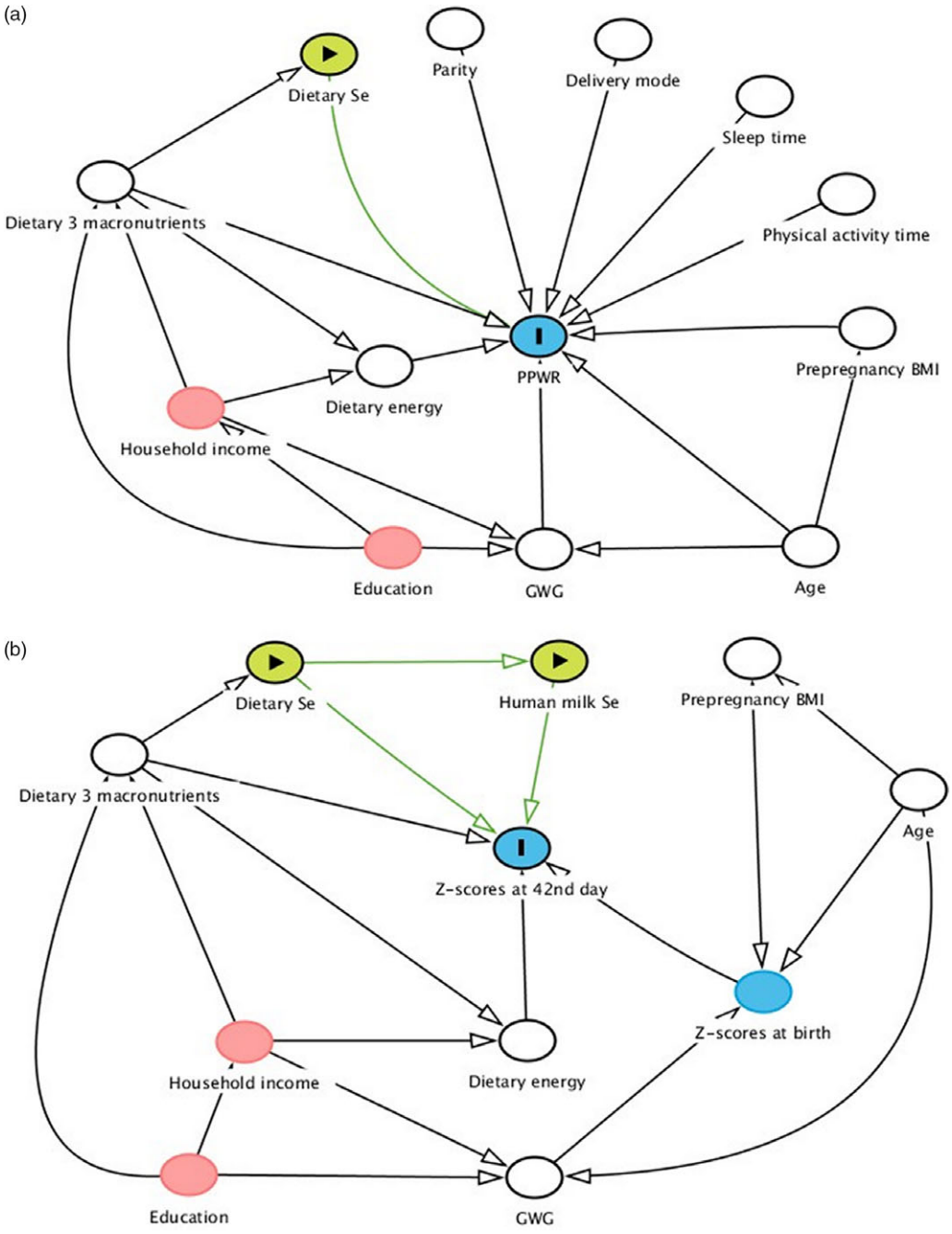

Fig. 2. Directed acyclic graph representing the causal assumptions used for covariate selection ((a) the multivariable linear regression analysis; (b) the multinomial logistic regression analysis). ⊙, Exposure; ⊙, outcome; ⊙, ancestor of exposure; ⊙, ancestor of outcome; ⊙, ancestor of exposure and outcome; ⊙, adjusted variable; ⊙, unobserved (latent); ⊙, other variables; ▬, causal path. PPWR, postpartum weight retention; GWG, gestational weight gain.

($P = 0{\cdot}000$). No significant changes of *Z*-scores were found in group of insufficient Se intake ($P > 0{\cdot}05$). Consistent with infants at birth, most of all infant at 42nd day have adequate WLZ, LAZ and WAZ (77·27 %, 89·02 % and 96·97 %, respectively).

Our results indicated that each 1 kg of increase in GWG of mother was related to OR of 0·902 (95 % CI 0·878, 0·925) in underweight and 0·915 (95 % CI 0·844, 0·990) in wasting of her child, while each unit of increase in prepregnancy BMI was associated with OR of 0·887 (95 % CI 0·803, 0·970) in underweight and 0·798 (95 % CI 0·666, 0·955) in wasting of her infant ($P < 0{\cdot}05$, Table 6).

Multinomial logistic regression was conducted to estimate the associations of maternal Se nutritional status with their infant's *Z*-scores (normal level *Z*-scores as a reference group) at 42nd day. Table 7 lists the OR of growth abnormally associated with dietary intake of Se and Se content in milk of their mothers. Just only WLZ was associated with dietary Se intake and Se level in breast milk ($P < 0{\cdot}05$).

Table 1. Characteristics of socio-demographics by participants' daily dietary selenium intake (Mean values and standard deviations; numbers and percentages)

Characteristics	Total (*n* 264)		Insufficient Se intake (*n* 105)*		Optimal Se intake (*n* 66)†		Excessive Se intake (*n* 93)‡		*P*
	n	%	*n*	%	*n*	%	*n*	%	
Age§ (years)									0·064
Mean	27·01		27·31		27·78		26·47		
SD	5·3		4·9		4·0		5·9		
Education‖									
Junior and below	111	42·05	27	25·71	14	21·21	70	75·27	0·000
Senior	63	23·86	27	23·81	18	27·27	18	19·35	
College and above	90	34·09	51	50·56	34	51·52	5	5·38	
Annual per capita household income‖									
Low (<10 000 Chinese Yuan (CNY)/person per year)	53	20·08	9	8·57	4	6·06	40	43·01	0·000
Medium (10 000-30 000 CNY/person per year)	114	43·18	43	40·95	22	33·33	49	52·69	
High (>30 000 CNY/person per year)	97	36·74	53	50·48	40	60·61	4	4·30	
Physical activity time‖ (h/d)									0·001
Mean	3·13		3·12[a]		2·33[b]		3·47[a]		
SD	2·0		2·1		1·2		2·2		
Delivery mode‖									0·002
Vaginal delivery	115	43·56	47	44·76	25	37·88	43	65·15	
Forceps delivery	30	11·36	15	14·29	14	21·21	1	1·52	
Caesarean delivery	119	45·08	43	40·95	27	40·91	49	74·24	
Parity‖									0·000
Primiparous	192	72·73	90	85·71	60	90·90	42	45·16	
Multiparous	72	27·27	15	14·28	6	9·09	51	54·84	
Infant's sex‖									0·863
Boy	136	51·52	53	50·48	33	50·00	50	53·76	
Girl	128	48·48	52	49·52	33	50·00	43	46·24	

[a,b] Mean values within a row with unlike superscript letters were significantly different ($P < 0·05$).
* Subjects in this group have insufficient Se daily intake (<78 μg Se/d).
† Subjects in this group have optimal Se daily intake (78–400 μg Se/d).
‡ Subjects in this group have excessive Se daily intake (>400 μg Se/d).
§ Values expressed as means and standard deviations for continuous variables (compared by ANOVA and least significant difference).
‖ Values expressed as numbers and percentages for categorical data (compared by χ^2 test).

Table 2. Weight and BMI of participants by daily selenium intake (Mean values and standard deviations; numbers and percentages)

Characteristics	Total (*n* 264)		Insufficient Se intake (*n* 105)*		Optimal Se intake (*n* 66)†		Excessive Se intake (*n* 93)‡		*P*
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
Prepregnancy weight§ (kg)	55·69	7·9	56·73[a]	8·1	57·60[a]	8·5	53·18[b]	6·6	0·000
Prepregnancy BMI§ (kg/m^2)	21·74	3·6	21·90	4·7	21·79	2·4	21·51	2·7	0·706
Weight before delivery§ (kg)	70·42	9·2	72·32[a]	8·1	74·09[a]	8·9	65·69[b]	8·6	0·000
GWG§ (kg)	15·00	6·4	15·59[a]	5·4	17·08[a]	6·7	12·87[b]	6·6	0·000
Proportion of GWG categories‖									0·025
Insufficient weight gain									
n	57		19		11		27		
%	21·59		18·10		16·67		29·03		
Optimal weight gain									
n	119		47		26		46		
%	45·08		44·76		39·39		49·46		
Excess weight gain									
n	88		39		29		20		
%	33·33		37·14		43·94		21·51		
PPWR§¶ (kg)	6·81	6·6	8·17[a]	6·2	7·86[a]	6·3	4·49[b]	6·0	0·000

GWG, gestational weight gain; PPWR, postpartum weight retention.
[a,b] Mean values within a row with unlike superscript letters were significantly different ($P < 0·05$).
* Subjects in this group have insufficient Se daily intake (<78 μg Se/d).
† Subjects in this group have optimal Se daily intake (78–400 μg Se/d).
‡ Subjects in this group have excessive Se daily intake (> 400 μg Se/d).
§ Values expressed as means and standard deviations for continuous variables (compared by ANOVA and least significant difference).
‖ Values expressed as numbers and percentages for categorical data (compared by χ^2 test).
¶ At 42nd day postpartum.

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Table 3. Distribution of age, gestational weight gain (GWG), prepregnancy BMI, time of physical activity and sleep, dietary intakes of total energy, three macronutrients and selenium among early lactation women with postpartum weight retention (PPWR) quartiles
(Mean values and standard deviations; median values and percentiles)

	PPWR								
	25th		50th		75th		100th		
Items	Mean	SD	Mean	SD	Mean	SD	Mean	SD	*P*
Age* (years)	27·39	5·1	27·78	5·3	27·58	4·4	26·72	3·8	0·615
GWG† (kg)									0·000
Median	10·00^{d}		12·80^{c}		16·00^{b}		20·00^{a}		
Percentiles	7·00–13·00		11·00–15·00		15·00–18·00		15·00–25·00		
Prepregnancy BMI* (kg/m^2)	23·28^{a}	5·5	22·24^{a,b}	2·7	21·49^{b}	2·4	20·05^{c}	2·3	0·000
Dietary Se† (μg/d)									0·001
Median	577·77^{a}		92·05^{b}		83·53^{b}		74·77^{b}		
Percentiles	72·78–887·11		57·09–607·90		61·13–587·57		53·21–266·96		
Physical activity time†‡ (h/d)									0·067
Median	3·00		2·00		2·00		3·00		
Percentiles	2·00–4·00		1·00–3·00		1·00–3·00		2·00–4·00		
Sleep time* (h/d)	9·12	1·4	9·31	2·5	9·47	1·9	8·89	1·9	0·345
Energy* (kJ/d)	6104·69^{b}	1992·9	6330·72^{b}	2217·2	7167·18^{a}	2320·6	7287·65^{a}	2941·8	0·004
Dietary protein* (g/d)	85·58^{b}	34·9	84·25^{b}	37·9	95·48^{a,b}	33·3	104·53^{a}	48·0	0·005
(% energy)*	23·86^{a,b}	6·1	22·47^{b}	5·8	22·70^{a,b}	5·0	24·50^{a}	5·2	0·087
Dietary fat* (g/d)	46·40^{a,b}	22·8	43·16^{b}	22·6	49·46^{a,b}	23·9	51·63^{a}	29·1	0·171
(% energy)*	28·41^{a}	8·4	25·41^{b}	7·6	25·65^{b}	7·9	26·60^{a,b}	8·2	0·109
Dietary carbohydrate* (g/d)	244·84	79·2	277·62	65·3	245·99	87·4	232·84	86·9	0·412
(% energy)*	47·64^{b}	12·2	52·12^{a}	11·2	51·65^{a}	10·3	48·84^{a,b}	11·0	0·046

^{a,b,c,d} Values within a row with unlike superscript letters were significantly different ($P < 0·05$).
* Values expressed as means and standard deviations for continuous variables (compared by ANOVA and least significant difference).
† Values expressed as medians and 25th and 75th percentiles for skewed data (compared by Kruskal–Wallis and Mann–Whitney *U* test).
‡ Physical activity is any physical activity.

Table 4. Association of postpartum weight retention with dietary selenium intake*†
(Coefficient values and 95 % confidence intervals)

	B	95 % CI	*P*
Crude model	−0·004	−0·006, −0·002	0·000
Adjusted model	−0·002	−0·003, 0·000	0·039

* Covariates are following: gestational weight gain (kg), prepregnancy BMI, dietary intakes of protein fat (g/d), carbohydrate (g/d) and total energy (kJ/d), age (years), parity, and time of physical activity (h/d) and sleep (h/d).
† Results were observed by multivariable linear regression analyses.

Discussion

Nowadays, more and more evidence shows that PPWR can develop into overweight and obesity, which is harmful to women health for a long time, and PPWR is also associated with adverse neonatal outcomes[1,9]. Unexpectedly, in this study, Se levels in lactating mothers were also found to be negatively related to PPWR ($P < 0·05$). Reasonable? Many studies reported the relationship between serum/plasma Se and BMI or the prevalence of obesity in many countries, the results of which were contradictory. For example, in a study involving 6440 men and 6849 women from the USA, serum Se levels were inversely associated with increased BMI with −4 (95 % CI −5·5, −1·6) ng/ml and difference between the highest and the lowest quartiles was statistically significant[60]. A detailed examination of 573 school-age children from Madrid also demonstrated that both serum Se and Se intake of overweight children (BMI > P85) were 14 % and 27 %, respectively, lower than normal-weight children[61]. Conversely, a cross-sectional study of 245 adolescent girls from rural Vietnam suggested that BMI < 17 kg/m^2 (OR 2·65, 95 % CI 1·25, 5·61) was found to be a risk factor for low serum Se levels (<70 ng/ml), but this was likely a reflection of poor nutritional intake[27]. A case–control study on Chinese adults suggested that, obesity, rather than insulin resistance, is central to the increase in selenoprotein P (SELENOP) level in serum[28]. However, several previous studies indicated that BMI was not associated with circulating Se concentrations[62,64]. The underlying mechanism remains to be clarified.

In vitro, several studies have demonstrated that Se had an essential role in adipogenesis[65,73]. *In vivo*, both low- and over-expression of adipocyte selenoproteins may result in adipose tissue dysfunction contributing to adipocyte hypertrophy or dystrophy, IR and adipose tissue inflammation[74]. The proposed role of Se in adipose tissue physiology and obesity pathogenesis is shown in Appendix 3[75,80]. Adequate Se supply (including its transport with SELENOP), as well as normal selenoprotein expression, is essential for regulation of adipogenesis and physiological development of adipose tissue, further influencing its physiological functioning, including energy storage, endocrine and immune functions[81,82].

Adenosine monophosphate-activated protein kinase is an energy status sensor that controls cellular energy homoeostasis and activates energy production processes by stimulating catabolic pathways and inactivating processes involved in ATP consumption[83]. GPX1 and/or SELENOP inhibited phosphorylation (activation) of key mediators, such as Akt and adenosine monophosphate-activated protein kinase, in energy metabolism in liver and/or skeletal muscle[37].

Table 5. *Z*-scores of weight-for-length (WLZ), length-for-age (LAZ) and weight-for-age (WAZ) of infants at birth and 42nd day by daily selenium intake of their mothers (Mean values and standard deviations; numbers and percentages)

	At birth									At 42nd day								
	Total (*n* 264)		Insufficient Se intake (*n* 105)		Optimal Se intake (*n* 66)		Excessive Se intake (*n* 93)			Total (*n* 264)		Insufficient Se intake (*n* 105)		Optimal Se intake (*n* 66)		Excessive Se intake (*n* 93)		
Z-scores	*n*	%	*n*	%	*n*	%	*n*	%	*P*	*n*	%	*n*	%	*n*	%	*n*	%	*P*
WLZ†									0·300									0·000
Mean	−0·45		−0·35		−0·36		−0·56			−0·28		−0·21[a]		−1·05[b]**		0·11[a]**		
SD	1·4		1·3		1·1		1·3			1·7		1·8		1·6		1·7		
WLZ < −2‡	25	9·47	11	10·48	5	7·58	9	9·68		40	15·15	15	14·29	20	30·30	7	7·53	
−2 ≤ WLZ ≤ 2‡	236	89·39	93	88·57	60	90·91	83	89·25		204	77·27	83	79·05	44	66·67	75	80·65	
WLZ > 2‡	3	1·14	1	0·95	1	1·52	1	1·08		20	7·58	7	6·67	2	3·03	11	11·83	
LAZ†									0·004									0·000
Mean	0·37		0·39[a]		0·39[a]		0·18[b]			0·28		0·43[b]		0·82[a]**		−0·21[c]**		
SD	1·5		0·5		0·5		0·8			1·2		1·3		1·0		1·1		
LAZ < −2‡	2	0·76	1	0·95	0		1	1·08		8	3·03	5	4·76	0		3	3·23	
−2 ≤ LAZ ≤ 2‡	260	98·48	103	98·10	66	100	91	97·84		235	89·02	92	87·62	57	86·36	86	92·47	
LAZ > 2‡	2	0·76	1	0·95	0		1	1·08		21	7·95	8	7·62	9	13·64	4	4·30	
WAZ†									0·009									0·341
Mean	−0·08		0·02[a]		0·02[a]		−0·25[b]			0·08*		0·17		−0·02		0·03*		
SD	0·9		0·9		0·8		0·9			1·0		0·9		0·8		1·1		
WAZ < −2‡	7	2·65	2	1·90	2	3·03	2	2·15		6	2·27	2	1·90	1	1·52	2	2·15	
−2 ≤ WAZ ≤ 2‡	255	96·59	102	97·14	63	95·45	90	96·77		256	96·97	102	97·14	65	98·48	90	96·77	
WAZ > 2‡	2	0·76	1	0·95	1	1·52	1	1·08		2	0·76	1	0·95	0		1	1·08	

[a,b,c] Mean values within a row with unlike superscript letters were significantly different ($P < 0·05$).
*$P < 0.05$, **$P < 0.01$ (differences between *Z*-scores of infants at birth and at 42nd day).
† Values expressed as means and standard deviations for continuous variables (compared by ANOVA and least significant difference).
‡ Values expressed as numbers and percentages for categorical data.

Table 6. Associations of infants' abnormal *Z*-scores categories at birth with maternal prepregnancy BMI and gestational weight gain (GWG)* (Odds ratios and 95 % confidence intervals)

Dependents	Factors	*B*	*P*	OR	95 % CI
WLZ < −2	Prepregnancy BMI	−0·226	0·014	0·798	0·666, 0·955
	GWG	−0·089	0·028	0·915	0·844, 0·990
WLZ > 2	Prepregnancy BMI	−0·319	0·519	0·727	0·276, 1·917
	GWG	−0·419	0·258	0·658	0·318, 1·360
LAZ < −2	Prepregnancy BMI	0·308	0·160	1·361	0·886, 2·091
	GWG	−0·184	0·082	0·832	0·676, 1·023
LAZ > 2	Prepregnancy BMI	0·005	0·979	1·005	0·686, 1·472
	GWG	−0·037	0·675	0·963	0·809, 1·147
WAZ < −2	Prepregnancy BMI	−0·032	0·042	0·887	0·803, 0·970
	GWG	−0·083	0·038	0·902	0·878, 0·925
WAZ > 2	Prepregnancy BMI	0·061	0·633	1·062	0·829, 1·362
	GWG	0·022	0·778	1·022	0·878, 1·189

WLZ, *Z*-scores of weight-for-length; LAZ, *Z*-scores of length-for-age; WAZ, *Z*-scores of weight-for-age.
* Covariates are following: age (years), parity and household income (Yuan (CNY)/person per year). The effects of change of mothers' weight on infant's *Z*-scores were estimated by multinomial logistic regression.

Table 7. Associations of infants' abnormal *Z*-scores categories at 42nd day with maternal daily selenium intake (μg/d) and selenium content in breast milk (μg/l)* (Odds ratios and 95 % confidence intervals)

Dependents	Factors	*B*	*P*	OR	95 % CI
WLZ < −2	Dietary Se	−0·001	0·014	0·999	0·998, 1·000
	Breast milk Se	−0·025	0·021	0·975	0·951, 0·999
WLZ > 2	Dietary Se	−0·002	0·055	0·998	0·996, 1·002
	Breast milk Se	−0·159	0·024	0·853	0·743, 0·980
LAZ < −2	Dietary Se	0·001	0·680	1·001	1·000, 1·003
	Breast milk Se	0·010	0·774	1·010	0·942, 1·083
LAZ > 2	Dietary Se	0·000	0·372	0·999	0·998, 1·001
	Breast milk Se	−0·016	0·687	0·984	0·910, 1·064
WAZ < −2	Dietary Se	0·003	0·345	1·003	0·997, 1·008
	Breast milk Se	0·045	0·168	1·046	0·981, 1·115
WAZ > 2	Dietary Se	0·003	0·417	1·003	0·996, 1·009
	Breast milk Se	−0·128	0·497	0·880	0·608, 1·273

WLZ, *Z*-scores of weight-for-length; LAZ, *Z*-scores of length-for-age; WAZ, *Z*-scores of weight-for-age.
* Covariates are following: age (years), parity, *Z*-scores at birth, daily dietary intake of total energy (kJ/d) and three macronutrients (g/d) and household income (Yuan (CNY)/person per year). The effects of maternal Se nutritional status on infant's *Z*-scores were estimated by multinomial logistic regression.

Moreover, insulin has a key role in the control of carbohydrate and lipid homoeostasis, inducing storage of metabolic fuels after food intake, and some selenoproteins (GPX and SELENOP) have recently found to take a part in IR, by reducing the reactive oxygen species needed in the insulin signalling process, and deactivating the energy status sensor adenosine monophosphate-activated protein kinase in liver[37,84]. The current concept on potential mechanisms underlying insulin-antagonistic actions of Se, GPX1 and SELENOP is shown in Appendix 4[85].

That is to say, the Se nutritional status of lactating Chinese women was found as one possible cofactor of their PPWR. However, whether this impact of Se is short-term adaptation or long-term impact and its potential mechanism needs further studies.

In this study, GWG and prepregnancy BMI of mother were the indicators of their infants' physical *Z*-scores at birth (Table 6). As far as we know, PPWR of these mothers came often from weight gain during pregnancy and weight gain during lactation. GWG of mother includes fetal tissue (related to the birth weight of her newborn) and placental tissues as well as weight gain. Similarly, weight gain during lactation includes weight of breast milk and weight gain during this period. PPWR is mainly from excessive weight gains during pregnancy and lactation, and it might have effects on the birth weight and weight gain during development of her offspring. Some previous studies also indicated that maternal blood Se concentration is regarded as a factor of small-for-gestational age newborns[50,86,87].

Also in our study, in addition to GWG and prepregnancy BMI, maternal Se intake and Se content in milk of mother also were the indicator of her infant's physical *Z*-scores at 42nd day postpartum (shown in Table 7): the optimal maternal Se intake and the rational Se content in milk have positive associations with growth and development of offspring ($P < 0·05$).

Se is related to the normal development of the body. First of all, it may directly participate in the normal formation and development of bones. Se deficiency can cause the prevalence of Kashin-Beck disease, but the underlying mechanism is unknown[88,89]. Of course, the interaction between Se and iodine promotes the development of the body, and its indirect mechanism is much clear: iodothyronine deiodinase, three selenoenzymes, can catalyse the conversion of thyroxine (T4) to active triiodothyronine (T3) as one of the critical hormones in normal growth and development of infant[90]. Thus, Se nutrition status could conceivably affect thyroid function in infants and further affect the growth of these infants, which was supported by some previous animal experiments[91,92].

Above all, some health policy should be formulated to prevent excessive maternal PPWR and abnormal *Z*-scores of infants. Initially, it is important to improve the quality of currently implemented general prenatal and postpartum care programmes, at the public health centres, especially those concerning nutritional guidelines. Care policy should include the following: (1) systematic weight surveillance throughout the entire gestational period; (2) specific nutritional counselling, such as healthy pregnancy diets appropriate for controlling GWG and postpartum diets considering Se dietary intake especially.

Several strengths of the current study should be noted; to the best of our knowledge, this is one of the first surveys to observe the relationship between dietary intakes of Se and PPWR in early lactating Chinese women as well as their offspring's physiological development. Several potential confounding variables were controlled in our analysis. Our research has several limitations. Causal inference cannot be drawn from this study because it is a cross-sectional study during the early short-term postpartum. Thus, whether the impact of Se obtained from our results is short-term adaptation or long-term impact and its potential mechanism needs further studies. Besides, we used WHO standards to evaluate the nutritional status of infants, which may be not appropriate for Chinese children, and some studies found the WHO growth standard was not suitable for any region and age[93,95]. Additionally, there is no specific formula for lactating Chinese women to calculate the dietary Se intake daily from the concentration of plasma Se and the little difference in bioavailablity of Se between non-lactating adult women and lactating adult women may lead to overestimate the daily dietary Se intake in these mothers.

Conclusions

In conclusion, daily Se intake of lactating women was related negatively to PPWR. If maternal pregnancy BMI or GWG was too low, the risk of offspring's developmental delay would be increased. In addition, the physical *Z*-scores at 42nd day of infants were associated with maternal dietary Se intakes and Se content in milk. Higher levels of daily Se intake and Se in milk of mothers could reduce the incidence of infant malnutrition. These results revealed that lactating women with a sufficient intake of proteins and total energy but lack of Se still had potential associations with excessive maternal PPWR and abnormal physical development of their offspring, and the causal relations should be confirmed by further longitudinal study.

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Supplementary material

For supplementary material referred to in this article, please visit https://doi.org/10.1017/S0007114521000015

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