Selenium status in UK pregnant women and its relationship with hypertensive conditions of pregnancy

Margaret P. Rayman1*, Sarah C. Bath1, Jacob Westaway2, Peter Williams3, Jinyuan Mao1, Jessica J. Vanderlelie2, Anthony V. Perkins2 and Christopher W. G. Redman4

1Department of Nutritional Sciences, Faculty of Health and Medical Sciences, School of Biosciences and Medicine, University of Surrey, Guildford GU2 7XH, UK
2School of Medical Science, Griffith Health Institute, Griffith University, Queensland, QLD 4222, Australia
3Department of Mathematics, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford GU2 7XH, UK
4Nuffield Department of Obstetrics and Gynaecology, University of Oxford, Oxford OX3 9DU, UK

(Submitted 10 June 2014 – Final revision received 13 October 2014 – Accepted 17 October 2014)

Abstract

Dietary intake/status of the trace mineral Se may affect the risk of developing hypertensive conditions of pregnancy, i.e. pre-eclampsia and pregnancy-induced hypertension (PE/PIH). In the present study, we evaluated Se status in UK pregnant women to establish whether pre-pregnant Se status or Se supplementation affected the risk of developing PE/PIH. The samples originated from the SPRINT (Selenium in Pregnancy Intervention) study that randomised 230 UK primiparous women to treatment with Se (60 μg/d) or placebo from 12 weeks of gestation. Whole-blood Se concentration was measured at 12 and 35 weeks, toenail Se concentration at 16 weeks, plasma selenoprotein P (SEPP1) concentration at 35 weeks and plasma glutathione peroxidase (GPx3) activity at 12, 20 and 35 weeks. Demographic data were collected at baseline. Participants completed a FFQ. UK pregnant women had whole-blood Se concentration lower than the mid-range of other populations, toenail Se concentration considerably lower than US women, GPx3 activity considerably lower than US and Australian pregnant women, and low baseline SEPP1 concentration (median 3.00, range 0.90–5.80 mg/l). Maternal age, education and social class were positively associated with Se status. After adjustment, whole-blood Se concentration was higher in women consuming Brazil nuts (P=0.040) and in those consuming more than two seafood portions per week (P=0.054). A stepwise logistic regression model revealed that among the Se-related risk factors, only toenail Se (OR 0.38, 95% CI 0.17, 0.87, P=0.049) and in those consuming more than two seafood portions per week (OR 0.049). In conclusion, UK women have low Se status that increases their risk of developing PE/PIH. Therefore, UK women of childbearing age need to improve their Se status.

Key words: Selenium status; Pregnancy; Hypertension; Hypertensive conditions of pregnancy

As many as 10% of women are affected by high blood pressure in pregnancy and some 2–5% will go on to develop proteinuria, triggering a diagnosis of the more serious hypertensive condition, i.e. pre-eclampsia (PE). Not only is PE associated with high maternal and fetal morbidity and mortality, women who have had PE, or indeed pregnancy-induced hypertension (PIH), have a greater risk of developing hypertension, stroke and IHD in later life. Furthermore, they have daughters who are at an increased risk of developing the same pregnancy complications and children who are more likely to develop hypertension as adults.

There are indications that dietary intake or status of the trace mineral Se may affect the risk of developing hypertensive conditions of pregnancy. For instance, Chinese women supplemented with Se have been shown to have a lower risk of developing PIH. A negative correlation has been found between Se status and the incidence of PE in an epidemiological study of forty-five countries. Significantly lower levels of selenoenzymes such as glutathione peroxidase (GPx) and thioredoxin reductase have been found in serum, plasma and placenta samples from pre-eclamptic women than in those from matched healthy controls. Genetic evidence suggests that the

Abbreviations: DBP, diastolic blood pressure; GPx, glutathione peroxidase; GPx3, plasma glutathione peroxidase; PE, pre-eclampsia; PIH, pregnancy-induced hypertension; SEPP1, selenoprotein P; Treg cells, regulatory T cells.

*Corresponding author: Professor M. P. Rayman, fax +44 1483 686401, email m.rayman@surrey.ac.uk
anti-inflammatory selenoprotein S (SELS) affects the risk of developing PE(16).

In a previous UK study, we have found that the concentration of Se in toenails (laid down from 3 to 12 months previously) of women with PE is significantly lower than that of matched controls ($P=0.001$)(17). That study triggered a pilot trial of Se supplementation in UK pregnant women that aimed to reduce biomarkers of PE risk(9). In that trial, we showed a significantly lower ($P=0.039$) concentration of plasma soluble vascular endothelial growth factor receptor-1 (sFlt-1), a recognised biomarker of pre-eclampsia risk, at 35 weeks in the Se-treated group (60 μg/d as Se yeast) than in the placebo group in participants of low Se status (lowest quartile) at baseline(9).

The present study used samples and data collected in that pilot trial. To establish the Se status, we used a range of measures at various gestational ages: (1) whole-blood Se concentration at baseline (12 weeks) and after 23 weeks of treatment with Se or placebo (35 weeks); (2) toenail Se concentration in clippings collected at 16 weeks (a measure of pre-pregnancy Se status); (3) plasma glutathione peroxidase (GPx3) activity at 12, 20 and 35 weeks; (4) plasma selenoprotein P (SEPP1) concentration at 35 weeks.

Our two hypotheses were that (1) UK pregnant women have low Se status, as determined by a number of parameters, and (2) pre-pregnant Se status or Se supplementation in pregnancy affects the risk of developing hypertensive conditions of pregnancy, i.e. PE or PIH, as a single outcome (PE/PIH).

**Experimental methods**

The selection of subjects has been described previously(9). Women were excluded if they were under 18 years, current smokers, taking any supplement containing Se, taking thyroid medication, had a multi-fetal pregnancy or a number of other specified pregnancy complications, or withheld consent. Blood, plasma and toenail samples originated from the SPRINT (Selenium in PRegnancy INTervention) study (trial registration no. ISRCTN37927591) that randomised 230 primiparous women in Oxford, UK, to treatment with Se (60 μg/d Se, as Se yeast) or placebo (placebo yeast) from their first hospital antenatal visit (mean gestational age 12-3 weeks) until the delivery of the baby(9). Blood samples, from which plasma was prepared, were collected at baseline (12 weeks), 20 and 35 weeks, while toenail clippings were collected at 16 weeks, as described previously(9).

A FFQ was administered at recruitment and was completed by 219 women (95.6% of the cohort). Meanwhile, clinical and demographic data, including weight and height (for calculation of BMI at baseline), date of birth (for calculation of maternal age at recruitment), age at which the education of the mother ceased, and occupation were recorded in order to explore the potential effect of a number of factors on Se status and on the development of PE/PIH.

PIH was defined as new hypertension appearing for the first time after 20 weeks of pregnancy. Hypertension was defined as diastolic blood pressure (DBP) ≥90 mmHg on two occasions (4 h apart). PE was defined as PIH and new-onset proteinuria after 20 weeks of pregnancy (≥300 mg/24 h or ≥2+ dipstick mid-stream urine/catheter specimen of urine). A protein:creatinine ratio of >30 mg/mmol of creatinine was generally used to confirm proteinuria. These criteria are an extension of those adopted by the International Society for the Study of Hypertension in Pregnancy(9,18).

The present study was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures involving human subjects were approved by the Milton Keynes Research Ethics Committee (REC reference no. 08/H0603/46). Written informed consent was obtained from all subjects.

**Selenium status measurements**

Whole-blood samples were stored at −20°C until thawed for analysis, and were analysed in duplicate. Se concentration was measured with full quality-control procedures by inductively coupled plasma-MS as described previously(9). The CV for the blood Se assay was 0.25% at 1.4 μmol/l and 0.17% at 3.0 μmol/l.

Toenail Se concentration was measured in clippings collected from all ten toes at 16 weeks. Toenails were prepared for analysis as described previously(17). Se content was determined using instrumental neutron activation analysis conducted at the Interfaculty Reactor Institute in Delft as described previously(17). The analysis of NIST SRM 1577b Bovine Liver gave a mean and combined standard uncertainty (forty-five determinations) of 0.73 (sd 0.005) mg/kg, compared with a certified mean of 0.74 (sd 0.02) mg/kg, indicating excellent accuracy of the method. The laboratory has an embedded quality-control system for quality assurance and management, which complies with the requirements of the International Standard ISO/IEC 17025:2005 and has been accredited by the Dutch Council for Accreditation since 1993.

SEPP1 concentrations were measured in the laboratory of Raymond Burk at the University of Vanderbilt using an ELISA as described previously(19). GPx3 activity was measured in plasma samples obtained at 12, 20 and 35 weeks at Griffith University as described previously(13). Briefly, GPx3 activity was measured spectrophotometrically in triplicate in 10 μl plasma samples. The rate of NADPH oxidation was recorded at 340 nm over 5 min using a Tecan Sunrise Absorbance Reader with Magellan Standard software (Tecan). The activity of GPx was calculated as units/l of plasma (one unit of activity was defined as 1 μmol of NADPH oxidised per min).

**Predictors of selenium status**

**Demographic factors.** Factors considered to be likely to affect Se status were as follows: baseline BMI; maternal age at recruitment; age at which the education of the mother ceased; occupation; ethnicity (Caucasian/other); smoking status (never smoked/ex-smoker). Occupation was used to code maternal...
Dietary factors. The FFQ containing eighteen items was based on the EPIC-Norfolk FFQ (21), and was designed to collect information on the consumption of the following Se- and iodine-rich foods: seafood (white, oily and shellfish, fish fingers, and fish roe); meat (beef, beef burgers, pork and lamb, bacon, ham, sausages, and corned beef); poultry; Brazil nuts; offal (liver and liver products); dairy products (grouped as one item in the questionnaire); milk. Where participants had not given a frequency of consumption for individual food items in the FFQ (n 7), these foods were coded as ‘never or rarely’. The answers were converted to weekly portions, and for seafood, meat and poultry, the portions were summed to give a total. Food items were then recoded to reflect a high and low intake of the food item, i.e. intake above and below the median. For liver products and Brazil nuts, participants were dichotomised into either ‘consumers’ (any frequency of consumption) or ‘non-consumers’ (those who answered as ‘never/rarely’ consuming the products) due to small number of consumers.

Statistical analyses

Whole-blood Se, toenail Se and SEPP1 concentrations and GPx3 activity were not normally distributed, hence data are presented as medians and range values. Mann–Whitney U tests were used to compare the concentrations/activity between the Se-treated and placebo groups.

The Wilcoxon matched-pair test was used to compare the changes in GPx3 activity from 12 to 20 weeks, 12 to 35 weeks and 20 to 35 weeks, and the change in whole-blood Se concentration from 12 to 35 weeks in the Se-treated and placebo groups.

Correlations were analysed by Spearman’s rank correlation test. The Mann–Whitney test was used to compare the differences in whole-blood Se and toenail Se concentrations between the groups. A general linear model was used on log-transformed whole-blood Se and toenail Se concentrations to adjust the dietary analysis by those demographic factors that were significantly associated with Se status in univariate analysis. A series of models was constructed where each individual dietary factor was entered separately into a model, with social class, maternal age and age at which the education of the mother ceased being confounders.

We explored the effect of known (7) and potential Se-related risk factors individually on the development of PE and PIH combined (PE/PIH) by multiple logistic regression. Factors that showed significance individually were then entered into a forward logistic regression model.

Subgroup analysis by compliance. A small number of women (n 9) in the Se-treated group took very few tablets (≤ 25 %). All the other women took 60 % or more of those they could have taken (expressed as a percentage of the number of days between starting treatment and the delivery of the baby); hence, the forward logistic regression modelling was repeated after excluding Se-treated women who took < 60 % of their treatment pills.

Significance was set at P ≤ 0·05, and analyses were conducted using the Statistical Package for the Social Sciences (version 21·0, SPSS, Inc.).

Results

Selenium status

Baseline measurements. Toenail Se concentration (16 weeks) and pre-treatment GPx3 activity (12 weeks) are presented in Table 1. There were no significant differences observed between the two treatment groups at baseline. Previously published (9) pre-treatment values of whole-blood Se concentration (12 weeks) in the same study are also presented in Table 1 to complete the dataset of Se status.

Baseline whole-blood Se concentration (12 weeks) was significantly correlated with the concentration of Se in toenails clipped at 16 weeks (Spearman’s ρ = 0·447, P < 0·001), as shown in Fig. 1, but not with GPx3 activity measured at 12 weeks (Spearman’s ρ = 0·042, P = 0·533).

Toenail Se concentration was significantly negatively, albeit weakly, correlated with DBP at baseline (Spearman’s ρ = −0·135, P = 0·047).

Effect of treatment on selenium status and plasma glutathione peroxidase activity. Table 1 presents the data for GPx3 activity measured at 20 and 35 weeks. Previously published (9) Se concentration in whole blood at 35 weeks and SEPP1 concentration in plasma at 35 weeks following treatment with Se or placebo are also presented for completeness.

There was no significant difference observed in GPx3 activity between the Se-treated and placebo groups at either 20 or 35 weeks. However, using the Wilcoxon matched-pair test, GPx3 activity increased in the Se-treatment group only, from 12 to 20 weeks (P = 0·025) and from 12 to 35 weeks (P = 0·014), although there was no further increase in the activity from 20 to 35 weeks (P = 0·219).

Effect of demographic and dietary factors on selenium status. Baseline whole-blood Se and toenail Se concentrations were significantly correlated, though weakly, with maternal age (Spearman’s ρ = 0·18, P = 0·006 and ρ = 0·16, P = 0·018, respectively) and with age at which the education of the mother ceased (Spearman’s ρ = 0·17, P = 0·009 and ρ = 0·20, P = 0·004, respectively).

The effect of other demographic and dietary factors on Se status is summarised in Table 2. Women who were classified as middle class and above had a significantly higher Se status as measured in both whole blood and toenails than those classified as lower middle class and below. Se status was not significantly affected by smoking status (never smoker or ex-smoker), ethnicity or BMI.

Whole-blood and toenail Se concentrations were significantly higher in consumers of Brazil nuts (P = 0·005 and P = 0·03, respectively); however, after adjusting for demographic factors, the difference in toenail Se concentration lost significance. Women who reported consuming at least two portions of seafood (white fish, oily fish or other seafood) per week had a
Table 1. Selenium status in UK pregnant women at 12 (baseline), 20 and 35 weeks of gestation  
(Median values and ranges)

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Women (n)</th>
<th>Placebo group</th>
<th>Se group</th>
<th>P&lt;sub&gt;t&lt;/sub&gt; (placebo group v. Se group)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All participants</td>
<td>Placebo group</td>
<td>Se group</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Median</td>
<td>Range</td>
<td>Median</td>
</tr>
<tr>
<td>Whole-blood Se concentration (μmol/l)&lt;sup&gt;‡&lt;/sup&gt;</td>
<td>229</td>
<td>12</td>
<td>1.31</td>
<td>0.84–3.33</td>
</tr>
<tr>
<td>Toenail Se concentration (µg/g)§</td>
<td>218</td>
<td>16</td>
<td>0.61</td>
<td>0.46–1.11</td>
</tr>
<tr>
<td>GPx&lt;sub&gt;3&lt;/sub&gt; activity (units/l)</td>
<td>227</td>
<td>12</td>
<td>72.4</td>
<td>42.5–141.9</td>
</tr>
<tr>
<td>GPx&lt;sub&gt;3&lt;/sub&gt; activity (units/l)</td>
<td>221</td>
<td>20</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Whole-blood Se concentration (μmol/l)&lt;sup&gt;‡&lt;/sup&gt;</td>
<td>215</td>
<td>35</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Plasma SEPP1 concentration (mg/l)&lt;sup&gt;‡&lt;/sup&gt;</td>
<td>215</td>
<td>35</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

GPx<sub>3</sub>, plasma glutathione peroxidase; NA, not applicable; SEPP1, selenoprotein P.

*P value for difference in GPx activity in Se group by Wilcoxon matched pairs test (12 v. 20 weeks) = 0.025; **P value for difference in GPx activity in Se group by Wilcoxon matched pairs test (12 v. 35 weeks) = 0.0005; ***P value for difference in whole-blood Se in placebo and Se groups by Wilcoxon matched pairs test (12 v. 35 weeks) = 0.0001.

†P values were obtained from the Mann–Whitney test comparing the differences between the treatment groups.

‡Previously published data from the same study(9). The P value for whole-blood Se concentration at 12 weeks differs from that reported in Rayman et al. (0.054). Intake of dairy products, meat and poultry, or liver did not significantly affect whole-blood Se concentration. However, cows' milk was associated with toenail Se concentrations, which were significantly higher in women who drank cows' milk (OR 1.5, 95% CI 1.03, 1.18) than in those who did not, but this association lost significance after adjustment.

§Toenails were clipped at approximately 16 weeks of gestation so Se concentration in clippings would have been unaffected by Se treatment and reflects pre-pregnancy status.
British Journal of Nutrition

0·61
16 weeks of gestation (laid down before conception) was in the few other populations for whom data were available. Hence, whole-blood Se concentration in our pregnant population was a little lower than the middle of the range observed in women from The Netherlands (mean 0·58–0·72 µmol/l) found in the present study for the placebo group at 35 weeks of gestation. The median baseline GPx3 activity was 72·4 units/l (Table 1). This is considerably lower than other values of GPx3 activity measured in other studies of pregnant women in the same laboratory, i.e. mean GPx3 activities of 84 and 104 units/l were found in cohorts of US and Australian women in the second trimester of pregnancy, respectively (Vanderlelie et al., unpublished results). These values can more properly be compared with the value of 75·4 units/l reported in the present study for the placebo group in the second trimester. Hence, it can be concluded that GPx3 activity was low in this UK pregnant population, probably reflecting a Se intake that is insufficient to optimise plasma GPx activity.

Women who were older, of higher social class (based on occupation) and left education at a later age had significantly higher Se status (whole blood and toenails). These findings are in agreement with those of the 2001 Adult UK National Diet and Nutrition Survey where higher plasma Se concentration was associated with older age, better education and higher earnings (P≤0·001).

With regard to diet, the consumption of Brazil nuts, known to be high in Se, significantly increased whole-blood Se concentration, although its significant effect on toenail Se concentration disappeared after adjustment; however, the number of Brazil nut consumers was small (n 26). The consumption of seafood tended to increase both whole-blood and toenail Se concentrations.

Discussion

Baseline selenium status

We chose to measure whole-blood Se concentration rather than serum/plasma Se concentration, as it is a longer-term measure of Se status and therefore less subject to day-to-day variation. However, this means that we have fewer pregnancy data with which to compare our values. There is only one reported first-trimester value of approximately (read from a graph) 1·0 µmol/l, which is lower than our baseline (12-week) value of 1·31 µmol/l, but it was reported from a study in Serbia, a known low-Se area. Other reported values are from the third trimester until delivery, and range from 0·76 to 0·8 in Serbia, 1·30 to 1·36 in Kuwait, to 1·51 µmol/l in Da-Ye, China, and can be compared with the median value of 1·16 µmol/l found in the present study for the placebo group at 35 weeks of gestation. Hence, whole-blood Se concentration in our pregnant population was a little lower than the middle of the range observed in the few other populations for whom data were available.

The median toenail Se concentration in clippings taken at 16 weeks of gestation (laid down before conception) was 0·61 µg/g, almost identical to the median value of 0·62 µg/g found in pregnant controls in our previous study. This value is similar to that of toenail Se concentrations measured in women from The Netherlands (mean 0·58–0·72 µg/g), but considerably lower than in women from the USA (mean 0·75–0·92 µg/g).

The median baseline GPx3 activity was 72·4 units/l (Table 1). This is considerably lower than other values of GPx3 activity measured in other studies of pregnant women in the same laboratory, i.e. mean GPx3 activities of 84 and 104 units/l were found in cohorts of US and Australian women in the second trimester of pregnancy, respectively (Vanderlelie et al., unpublished results). These values can more properly be compared with the value of 75·4 units/l reported in the present study for the placebo group in the second trimester. Hence, it can be concluded that GPx3 expression pattern occurs during deprivation and supplementation states. Furthermore, as mitochondrial oxidative stress increases over the course of pregnancy, intracellular...
GPx isoforms may be preferentially expressed over extracellular GPx3 for the protection of the trophoblast (34, 35).

Risk of development of hypertensive conditions of pregnancy

We combined the outcomes of PE and PIH because the distinction between the two is not always completely clear; 15–45 % of women with PIH will eventually develop PE (36, 37), particularly when PIH presents early in gestation (38). Indeed, PIH associated with features of PE other than proteinuria, such as hyperuricaemia or intra-uterine growth retardation, is now regarded as an atypical variant of PE (39). Furthermore, there are immunological similarities between the conditions, both of which show a general depression in immunocompetent lymphocytes with a higher overall level of T-cell activation (40), suggesting some commonality in aetiology. Increased oxidative stress is also a feature observed in both conditions (41, 42).

We previously found that women supplemented with Se had a significantly lower risk of the combined hypertensive outcomes than those treated with placebo (adjusted OR 0.35, P=0.044) (9). PE is associated with increased systemic (vascular) inflammation relative to normal pregnancy (43); although this has not been shown for PIH as such, the effect of Se on the risk of developing PE/PIH may be partly due to the ability of selenoproteins to counteract inflammation (44, 45). Se supply is known to affect the synthesis and actions of eicosanoids, important modulators of inflammation, platelet activation, blood pressure and the immune response (44, 45); for instance, under oxidative stress, Se-deficient endothelial cells produce less of the vasodilatory eicosanoid, prostacyclin (45).

A further important anti-inflammatory mechanism of Se involves selenoprotein S (SELS). SELS manages inflammation control in the endoplasmic reticulum by assisting in the retrotranslocation of misfolded proteins from the endoplasmic reticulum into the cytosol (46). Endoplasmic-reticulum stress is known to be involved in the pathophysiology of PE (47). A SNP in the gene encoding SELS has been correlated with serum concentrations of pro-inflammatory cytokines (48) and with the risk of developing PE in a large Norwegian cohort (16).

Of the known risk factors for hypertensive conditions of pregnancy (7) treated individually, only baseline DBP and

### Table 2. Predictors of selenium status

<table>
<thead>
<tr>
<th>(Number of women; median values and interquartile ranges)</th>
<th>12-week whole-blood Se (μmol/l)</th>
<th>Toenail Se (μg/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Women (n) Median Interquartile range P Adjusted P</td>
<td>Women (n) Median Interquartile range P Adjusted P</td>
</tr>
<tr>
<td>Demographic factors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Social class</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle and above</td>
<td>101 1.33 1.22–1.48 0.027 NA†</td>
<td>98 0.63 0.59–0.69 0.004 NA†</td>
</tr>
<tr>
<td>Lower middle and below</td>
<td>128 1.30 1.14–1.45</td>
<td></td>
</tr>
<tr>
<td>Smoking status</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Never smoked</td>
<td>156 1.32 1.19–1.47 0.529 NA†</td>
<td>148 0.61 0.57–0.67 0.261 NA†</td>
</tr>
<tr>
<td>Ex-smoker</td>
<td>73 1.30 1.18–1.46</td>
<td></td>
</tr>
<tr>
<td>Ethnicity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caucasian</td>
<td>213 1.31 1.18–1.47 0.438 NA†</td>
<td>202 0.61 0.56–0.67 0.869 NA†</td>
</tr>
<tr>
<td>Other</td>
<td>16 1.34 1.25–1.48</td>
<td></td>
</tr>
<tr>
<td>BMI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;25 kg/m²</td>
<td>138 1.35 1.19–1.48 0.183 NA†</td>
<td>131 0.61 0.56–0.67 0.841 NA†</td>
</tr>
<tr>
<td>≥25 kg/m²</td>
<td>91 1.29 1.16–1.44</td>
<td></td>
</tr>
<tr>
<td>Dietary factors</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seafood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;2 portions/week</td>
<td>98 1.27 1.14–1.41 0.101 NA† 0.054</td>
<td>95 0.59 0.54–0.65 0.012 0.078</td>
</tr>
<tr>
<td>≥2 portions/week</td>
<td>121 1.36 1.21–1.48</td>
<td></td>
</tr>
<tr>
<td>Meat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;7 portions/week</td>
<td>108 1.33 1.19–1.47 0.540 0.299</td>
<td>107 0.61 0.56–0.66 0.729 0.610</td>
</tr>
<tr>
<td>≥7 portions/week</td>
<td>111 1.30 1.16–1.46</td>
<td></td>
</tr>
<tr>
<td>Brazil nuts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-consumer</td>
<td>193 1.30 1.16–1.46 0.005 0.040</td>
<td>187 0.60 0.56–0.66 0.034 0.147</td>
</tr>
<tr>
<td>Consumer</td>
<td>26 1.40 1.31–1.61</td>
<td></td>
</tr>
<tr>
<td>Offal (liver)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-consumer</td>
<td>182 1.31 1.18–1.47 0.583 0.765</td>
<td>176 0.61 0.56–0.66 0.702 0.804</td>
</tr>
<tr>
<td>Consumer</td>
<td>37 1.35 1.22–1.45</td>
<td></td>
</tr>
<tr>
<td>Dairy products</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;1 portion/d</td>
<td>110 1.30 1.16–1.45 0.423 0.672</td>
<td>107 0.61 0.56–0.67 0.916 0.112</td>
</tr>
<tr>
<td>&gt;1 portion/d</td>
<td>109 1.32 1.19–1.48</td>
<td></td>
</tr>
<tr>
<td>Cows’ milk</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;280 ml/d</td>
<td>146 1.32 1.18–1.46 0.920 0.983</td>
<td>144 0.60 0.56–0.66 0.016 0.083</td>
</tr>
<tr>
<td>≥280 ml/d</td>
<td>73 1.32 1.21–1.46</td>
<td></td>
</tr>
</tbody>
</table>

NA, not applicable.
* Conducted on log-transformed Se variables; a series of general linear models were constructed where each individual dietary factor was entered into a separate model, with maternal age, age at which the education of the mother ceased and social class (dichotomised) being confounders.
† Demographic factors were used to adjust the P values for the dietary factors only.
Unadjusted and adjusted risk factors for the development of pre-eclampsia (PE)/pregnancy-induced hypertension (PIH) determined by logistic regression

Table 3.

<table>
<thead>
<tr>
<th>Risk factors</th>
<th>Unadjusted model*</th>
<th>Adjusted model 1†</th>
<th>Adjusted model 2‡</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Women (n)</td>
<td>OR</td>
<td>95 % CI</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-----------</td>
<td>--------</td>
<td>---------</td>
</tr>
<tr>
<td>Baseline diastolic BP</td>
<td>227</td>
<td>1.14</td>
<td>1.07, 1.21</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>227</td>
<td>1.20</td>
<td>1.09, 1.32</td>
</tr>
<tr>
<td>Toenail Se, 16 weeks (μg/g)</td>
<td>217</td>
<td>0.34</td>
<td>0.16, 0.72</td>
</tr>
<tr>
<td>Treatment (Se v. placebo)</td>
<td>227</td>
<td>0.39</td>
<td>0.15, 1.06</td>
</tr>
<tr>
<td>Age (years)</td>
<td>227</td>
<td>0.99</td>
<td>0.88, 1.10</td>
</tr>
<tr>
<td>History of PE in mother</td>
<td>227</td>
<td>0.67</td>
<td>0.08, 5.38</td>
</tr>
<tr>
<td>History of PE in sister</td>
<td>227</td>
<td>1.76</td>
<td>0.20, 15.42</td>
</tr>
<tr>
<td>Whole-blood Se, 12 weeks (μmol/l)</td>
<td>227</td>
<td>0.61</td>
<td>0.13, 2.52</td>
</tr>
<tr>
<td>Whole-blood Se, 35 weeks (μmol/l)</td>
<td>215</td>
<td>0.39</td>
<td>0.13, 1.22</td>
</tr>
<tr>
<td>SEPP1, 35 weeks (mg/l)</td>
<td>215</td>
<td>0.72</td>
<td>0.51, 1.01</td>
</tr>
</tbody>
</table>

BP, blood pressure; NA, not applicable; SEPP1, selenoprotein P.

* Risk factors for the development of PE/PIH assessed individually by logistic regression.
† Optimal model of risk factors for the development of PE/PIH assessed by forward logistic regression, including diastolic BP, BMI, toenail Se concentration and treatment.
‡ Optimal model of risk factors for the development of PE/PIH as in model 1, but excluding those Se-treated women who took <60% of their treatment pills.
§ Variable was not selected in the stepwise analysis.
| Variable multiplied by 10 for scaling purposes. |
Conclusion

We validated our first hypothesis that UK pregnant women have low Se status, as determined by the median value of a number of status parameters. We also validated our second hypothesis that Se status/Se supplementation affects the risk of developing hypertensive conditions of pregnancy; the odds of PE/PIH were significantly reduced in women with higher pre-pregnancy Se status (toenail Se) and in those supplemented with Se from 12 weeks of gestation.

In conclusion, UK women need to improve their Se status, ideally before pregnancy, as our data suggest that pre-pregnancy status has a significant effect on the risk of developing hypertensive conditions of pregnancy. Although our simplified FFQ revealed that consumption of Brazil nuts was associated with higher whole-blood Se concentration, we cannot recommend them as a means of increasing Se status as they contain both Ba, at a level where consumption of two nuts per d could exceed the reference dose, and Ra (Ra228), with an activity of 6–133 Bq/kg (62–64). Offal and seafood are other rich sources of Se (65) and higher consumption of seafood was marginally associated with better Se status; however, these foods are often unpopular. Hence, it is likely that many women will need to take a Se-containing supplement (e.g. as part of a multivitamin and mineral pregnancy supplement) at least as soon as they know they are pregnant, and preferably when planning pregnancy.

We gave a supplement of 60 mg Se/d; however, a dose of 100 μg Se/d would probably be sufficient in women who only commence supplementation when pregnancy is confirmed, as even at that higher dose, 60 d were required for a plateau to be reached in GPx3 activity (52).

A study in a larger cohort of pregnant women is needed to confirm these findings.

Acknowledgements

The authors are extremely grateful to all the women who took part in the study and the team at the John Radcliffe Hospital, especially Libby Searle, research midwife, who recruited the women. The authors thank Dr Christine Sieniawska of the Trace Element Unit, Southampton University Hospital NHS Trust for the analysis of Se in whole blood, the laboratory of Raymond Burk, University of Vanderbilt, for the analyses of SEPP1, and Mehmet Sarlar and Menno Blauw of TU Delft Reactor Institute for the analysis of toenails.

The present study was supported by the Wellcome Trust Project Grant 083918/Z/07/Z (to M. P. R., and C. W. G. R); Nestlé Nutrition Institute Fellowship (to J. M.); MRC Population Health Scientist Fellowship (to S. C. B.); SEPP1 analyses at the laboratory of Raymond Burk, University of Vanderbilt were supported by grant NIH ES02497; toenail analysis at TU Delft Reactor Institute was supported by the European Commission under the 7th Framework Programme through the ‘Research Infrastructures’ action of the ‘Capacities’ Programme (NMI3-II grant number 283883).

The authors’ contributions are as follows: M. P. R. and C. W. G. R. designed the research; J. W. measured GPx3 activity; S. C. B. advised on the data analysis and analysed the FFQ; P. W., S. C. B., J. M. and J. J. V. conducted the statistical analysis; M. P. R. wrote the paper; S. C. B., P. W. and C. W. G. R. revised the paper; M. P. R. had primary responsibility for final content. All authors read and approved the final manuscript.

None of the authors has any conflict of interest to declare.

References


