North-south gradients in plasma concentrations of B-vitamins and other components of one-carbon metabolism in Western Europe: results from the European Prospective Investigation into Cancer and Nutrition (EPIC) Study

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Published in: British Journal of Nutrition

DOI: 10.1017/S0007114512004990

2013

Link to publication

Citation for published version (APA):

Total number of authors: 41

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North–south gradients in plasma concentrations of B-vitamins and other components of one-carbon metabolism in Western Europe: results from the European Prospective Investigation into Cancer and Nutrition (EPIC) Study

Simone J. P. M. Eussen1,2*, Roy M. Nilsen2, Øivind Midttun4, Steinar Hustad2, Noortje IJssennagger5, Klaus Meyer4, Åse Fredriksen4, Arve Ulvik4, Per M. Ueland2,16, Paul Brennan7, Mattias Johansson7, Bas Bueno-de-Mesquita8,9, Paolo Vineis10, Shu-Chun Chuang10, Marie Christine Boutron-Ruault11, Laure Dossus11, Florence Perquier11, Kim Overvad12, Birgit Teucher13, Verena A. Grote15, Antonia Trichopoulou14,15, George Adarakis15, Maria Plada15, Sabina Sieri16, Rosario Tumino17, Maria Santucci de Magistris18, Martine M. Ros9,19, Petra H. M. Peeters10,20, Maria Luisa Redondo21, Raúl Zamora-Ros22, Maria-Dolores Chirlaque23,24, Eva Ardanaz24,25, Emily Sonestedt26, Ulrika Ericson26, Jörn Schneede27, Bethany van Guelpen28, Petra A. Wark10, Valentina Gallo10,29, Teresa Norat10, Elio Riboli10 and Stein Emil Vollset1

1Department of Public Health and Primary Health Care and Section for Pharmacology, Institute of Medicine, Faculty of Dentistry and Medicine, University of Bergen, 5021 Laboratory Building, 9th Floor, Bergen, Norway
2Section for Pharmacology, Institute of Medicine, University of Bergen, Bergen, Norway
3Centre for Clinical Research, Haukeland University Hospital, Bergen, Norway
4Bevital A/S, Bergen, Norway
5Division of Human Nutrition, Wageningen University, Wageningen, The Netherlands
6Laboratory of Clinical Biochemistry, Haukeland University Hospital, Bergen, Norway
7International Agency for Research on Cancer, Lyon, France
8National Institute for Public Health and the Environment (RIVM), Bilthoven, The Netherlands
9Department of Gastroenterology and Hepatology, University Medical Centre, Utrecht, The Netherlands
10Department of Epidemiology and Biostatistics, School of Public Health, Faculty of Medicine, Imperial College, London, UK
11Inserm, Centre for Research in Epidemiology and Population Health, U1018, Institut Gustave Roussy, F-94805, and Paris South University, UMRS 1018, F-94805 Villejuif, France
12Section of Epidemiology, Department of Public Health, Aarhus University, Aarhus, Denmark
13German Cancer Research Center (DKFZ), Heidelberg, Germany
14WHO Collaborating Center for Food and Nutrition Policies, Department of Hygiene, Epidemiology and Medical Statistics, University of Athens Medical School, Athens, Greece
15Hellenic Health Foundation, Athens, Greece
16Nutritional Epidemiology Unit, Fondazione IRCCS Istituto Nazionale Tumori, Milano, Italy
17Cancer Registry and Histopathology Unit, “Civile – M.P. Arezzo” Hospital, ASP, Ragusa, Italy
18Department of Clinical and Experimental Medicine, Federico II University, Naples, Italy
19Department of Epidemiology, Biostatistics and IITA, Radboud University Nijmegen Medical Centre, Nijmegen, The Netherlands
20Julius Center, University Medical Center, Utrecht, The Netherlands
21Public Health Directorate, Asturias, Spain
22Unit of Nutrition, Environment and Cancer, Cancer Epidemiology Research Programme, Catalan Institute of Oncology (ICO-IDIBELL), Barcelona, Spain
23Department of Epidemiology, Murcia Regional Health Authority, Murcia, Spain

Abbreviations: CRC, colorectal cancer; EPIC, European Prospective Investigation into Cancer and Nutrition; GC, gastric cancer; LC, lung cancer; MMA, methylmalonic acid; MTHFR, methylenetetrahydrofolate reductase; PC, pancreatic cancer; PL, pyridoxal; tHcy, total homocysteine.

* Corresponding author: S. J. P. M. Eussen, fax +47 55 97-4605, email simone.eussen@farm.uib.no
Abstract

Different lifestyle patterns across Europe may influence plasma concentrations of B-vitamins and one-carbon metabolites and their relation to chronic disease. Comparison of published data on one-carbon metabolites in Western European regions is difficult due to differences in sampling procedures and analytical methods between studies. The present study aimed, to compare plasma concentrations of one-carbon metabolites in Western European regions with one laboratory performing all biochemical analyses. We performed the present study in the European Prospective Investigation into Cancer and Nutrition (EPIC) cohort among 5446 presumptively healthy individuals. Quantile regression was used to compare sex-specific median concentrations between Northern (Denmark and Sweden), Central (France, Germany, The Netherlands and United Kingdom) and Southern (Greece, Spain and Italy) European regions. The lowest folate concentrations were observed in Northern Europe (men, 10.4 nmol/l; women, 10.7 nmol/l) and highest concentrations in Central Europe. Cobalamin concentrations were slightly higher in Northern Europe (men, 350 pmol/l; women, 352 pmol/l) compared with Central and Southern Europe, but did not show a clear north–south gradient. Vitamin B6 concentrations were highest in Northern Europe (men, 22.2 nmol/l; women, 26.0 nmol/l) and decreased towards Southern Europe ($P_{\text{trend}} < 0.001$). Vitamin B12 concentrations were highest in Central Europe in men (77.3 nmol/l) and highest in the North among women (70.4 nmol/l), with decreasing concentrations towards Southern Europe in women ($P_{\text{trend}} < 0.001$). In men, concentrations of serine, glycine and sarcosine increased from the north to south. In women, sarcosine increased from Northern to Southern Europe. These findings may provide relevant information for the study of regional differences of chronic disease incidence in association with lifestyle.

Key words: B-vitamins; Amino acids; One-carbon metabolism; Europe

One-carbon metabolism involves transfer of one-carbon units from the amino acids serine or glycine to tetrahydrofolate to form methylenetetrahydrofolate. Methylenetetrahydrofolate is either used for the synthesis of thymidine and purines, which are building blocks for DNA, or it is reduced to methyltetrahydrofolate, which re-methylates homocysteine to methionine. Methionine is activated to $S$-adenosylmethionine, the major methyl group donor for the methylation reactions of many substrates. The vitamins B$_{12}$, B$_{6}$ and B$_{12}$ function as cofactors for enzymes, catalysing the conversion of homocysteine to methionine or cystathionine and cysteine. Choline is another source of one-carbon units. It is converted to betaine, which in the liver and kidneys serves as a substrate in another reaction re-methylating homocysteine to methionine, with dimethylglycine as a product. Sarcosine is formed from dimethylglycine or during the metabolism of excess methionine, and can be further metabolised to glycine, which is an important source of serine.

B-vitamins, related amino acids and variants of genes coding for enzymes involved in one-carbon metabolism may influence cellular growth, differentiation and function, which provides plausible biological background that links one-carbon metabolism to various disease outcomes. Although results from observational and experimental studies have not always been consistent, the majority of studies suggest that B-vitamins and other components related to one-carbon metabolism are associated with neural tube defects, the metabolic syndrome, CVD, cognitive impairment, bone health and different types of cancer.

The methylenetetrahydrofolate reductase (MTHFR) $677C \rightarrow T$ polymorphism and lifestyle factors such as smoking and alcohol consumption may affect blood concentrations of B-vitamins and other components of one-carbon metabolism. There is a great diversity in dietary and lifestyle patterns among European countries, which are likely to influence plasma status of nutrients and the subsequent risk of morbidity and mortality. For example, a Mediterranean diet – rich in plant foods and folate – in combination with healthy lifestyle factors such as abstaining from smoking, moderate alcohol consumption and being physically active, has been associated with a lower mortality rate.

The European Prospective Investigation into Cancer and Nutrition (EPIC) and a number of multicentre studies have been conducted to investigate dietary intake or blood concentrations of B-vitamins as determinants of health in Europe. These studies show relatively low intake of B-vitamins in Scandinavian countries, the Netherlands, Germany and Greece. However, no major differences in B-vitamin intake across EPIC study centres have been observed. The SENeca (Survey in Europe on Nutrition and the Elderly, a Concerted Action) study showed large differences in plasma vitamin status between study centres, with vitamin B$_{12}$ concentrations being lowest in Greece and Denmark, but no clear
geographical patterns were observed. A summary of thirty-one European studies on plasma/serum B-vitamins revealed relatively low folate concentrations in Norway and Sweden, while lower vitamin B<sub>12</sub> concentrations were observed in the Netherlands, Germany, Czech Republic and Italy compared to other countries.

Data on plasma concentrations of components related to one-carbon metabolism in European countries are inconclusive. Comparison of plasma concentrations between individual European studies is difficult due to different blood sampling protocols and large inter-assay variability by laboratory methods used in different studies. The present study aimed to investigate patterns in plasma B-vitamin status, amino acids and related methylamines in Western European regions, while eliminating variability in sampling procedures and assay methods, as all biochemical analyses were carried out in citrate plasma by a single laboratory. With data on 5446 individuals from the EPIC cohort, this is the largest population to date to compare patterns across European regions and in a population with no mandatory fortification with folic acid or other B-vitamins.

Methods

Study population

The EPIC study investigates associations between diet, lifestyle and cancer risk among individuals recruited between 1992 and 2000 living in ten European countries. The present cross-sectional study comprises the control individuals who were matched to cancer cases participating in four nested case–control sub-studies on gastric-(GC, n 805), colorectal-(CRC, n 2408), lung- (LC, n 1778) and pancreatic cancer (PC, n 455). Matching criteria were sex, age group (±2·5 years), study centre and date of blood collection (all studies), and additionally for time of blood collection and fasting status in the PC study. Blood samples from EPIC-Oxford and EPIC-Norway centres were exposed to ambient temperatures for up to 48 h. As some B-vitamins and related metabolites are unstable under such conditions, all EPIC-Oxford (n 221) and EPIC-Norway (n 11) samples were excluded from the present analyses. Participants in the present study were from Greece (n 288), recruited from studies on GC (n 32), CRC (n 51), LC (n 182) and PC (n 23), Spain (n 638), recruited from studies on GC (n 107), CRC (n 238), LC (n 254) and PC (n 39), Italy (n 799), recruited from studies on GC (n 186), CRC (n 294), LC (n 277) and PC (n 42), France (n 133), recruited from studies on GC (n 10), CRC (n 60), LC (n 48) and PC (n 15), Germany (n 797) recruited from studies on GC (n 117), CRC (n 313), LC (n 312) and PC (n 55), The Netherlands (n 650), recruited from studies on GC (n 78), CRC (n 297), LC (n 237) and PC (n 380), United Kingdom (n 919), recruited from studies on GC (n 104), CRC (n 421), LC (n 350) and PC (n 44), Denmark (n 500, recruited from studies on GC (n 45), CRC (n 373), LC (n 0) and PC (n 84)) and Sweden (n 722, recruited from studies on GC (n 128), CRC (n 361), LC (n 118) and PC (n 115)). 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 ethical review boards from the International Agency for Research on Cancer; all local participating centres approved the study. Written informed consent was obtained from all the subjects.

Data collection

Blood sampling and laboratory analyses. In each of the recruitment centres, fasting (42·8 % (6·6 % in North, 30·7 % in Central and 5·5 % in Southern Europe) or non-fasting (47·2 % (6·8 % in North, 14·3 % in Central and 26·1 % in Southern Europe)) blood samples of at least 30 ml were drawn at baseline between March 1991 and April 1999. In 9·9 % (9·1 % in North, 0·7 % in Central and 0·1 % in Southern Europe) information on prandial status was missing. Samples were stored at 5–10°C, protected from light and transported to local laboratories for processing and aliquoting as previously described. In all countries, except Denmark and Sweden, blood was separated into 0·5 ml aliquots (serum, plasma, erythrocytes anduffy coat for DNA extraction) and stored into plastic CBS straws, which were heat sealed and stored in liquid N<sub>2</sub> (−196°C). Half of the aliquots were stored at the local study centre and the other half in the central EPIC biorepository at the International Agency for Research on Cancer (Lyon, France). In Denmark, aliquots of 1·0 ml were stored locally at −150°C under N<sub>2</sub> vapour. In Sweden, samples were stored at −80°C.

For the present study, blood samples collected into citrate plasma tubes were used for biochemical analyses in the laboratory of Bevital AS (http://www.bevital.no). The present study included B-vitamins (folate, vitamins B<sub>2</sub> and B<sub>6</sub> species, vitamin B<sub>12</sub> and its marker methylmalonic acid (MMA)), methylamines (choline, betaine and dimethylglycine) and amino acids (total homocysteine (tHcy), methionine, total cysteine, cystathionine, serine, glycine and sarcosine). Vitamin B<sub>2</sub> measures included plasma concentrations of riboflavin and FMN; pyridoxal-5-phosphate, pyridoxal (PL) and 4-pyridoxic acid were measures of vitamin B<sub>6</sub> status. Vitamin B<sub>12</sub> and B<sub>6</sub> species and methylamines were determined by LC–MS/MS, and MMA and amino acids by GC–MS/MS based on methylchloroformate derivatisation. Vitamin B<sub>12</sub> was determined with a Lactobacillus leichmannii microbiological method and plasma folate with a Lactobacillus casei microbiological method, both adapted to a microtitre plate format, and analysis was carried out on a robotic workstation (Micro-lab AT plus 2; Hamilton Bonaduz AG) Within-and between-day CV for folate were 3–20 % (50) and 3–20 % for vitamin B<sub>2</sub> vitamers, 6–22 % for vitamin B<sub>6</sub> vitamers, <5 % for vitamin B<sub>12</sub>, tHcy and MMA, <5 % for choline, betaine and dimethylglycine and <5 % for the remaining amino acids.

FMN was not measured in the LC study; serine, glycine and sarcosine were not measured in gastric- and colorectal studies; and the methylamines were not measured in LC and PC studies. The MTHFR 677C→T polymorphism (rs 1801133) was determined by matrix-assisted laser desorption/ionisation
time-of-flight MS\(^{37,38}\) in the studies on GC, CRC and LC. Data on the \(\text{MTHFR} \ 677C \rightarrow T\) polymorphism were available for 87.8% of the participants (664 missing).

**Descriptive variables.** Data on age, sex and information on lifestyle factors known to affect B-vitamin status, such as smoking status\(^{13}\) (never, former, current, missing) and alcohol consumption, were collected at enrolment in the study. Total alcohol consumption (pure ethanol in g/d) at baseline, which represented consumption over the 12 months before enrolment in the EPIC cohort, was determined from lifestyle questionnaires. The present study distinguishes between abstainers, very light or occasional consumers (0–1 g/d), moderate consumers (1–3 g/d), heavy consumers (3–10 g/d) and very heavy consumers (≥10 g/d). Data on total alcohol intake were available for 99.6% of the participants (twenty-two missing).

**Statistical methods**

Statistical analyses were conducted for the total study population, as well as within each European region (North: Sweden and Denmark; Central: France, United Kingdom, the Netherlands and Germany; South: Italy, Spain and Greece) and country. Using the PROC CORR SAS procedure, we calculated Spearman rank correlation coefficients between metabolites, adjusting (using a PARTIAL statement) for age, sex, sub-study and prandial status. Because riboflavin may be formed from FMN\(^{39}\), we considered the sum of riboflavin and FMN as a measure for vitamin B\(_2\) status. As PL may be metabolised between demographic and lifestyle groups distributed. Therefore, differences in crude concentrations of some metabolites across European regions were assessed by median (data not shown). The proportion of current smokers was lowest in the Central European countries (16%), and the proportion of individuals consuming ≥30 g alcohol/d was highest in the Southern European countries (22.2%) (Table 1). The prevalence of the \(\text{MTHFR} \ 677TT\) genotype was 17.9% in Southern Europe compared with 12.2% in Central Europe and 8.2% in Northern Europe (Table 1).

Spearman correlation coefficients \((\rho_s)\), adjusted for age, sex, sub-study and prandial status between the vitamin B\(_6\) species, ranged from 0.61 to 0.71, riboflavin correlated with FMN \((\rho_s = 0.26)\), vitamin B\(_{12}\) with MMA \((\rho_s = -0.26)\) and tHcy \((\rho_s = -0.24)\) and folate with tHcy \((\rho_s = -0.30)\), all \(P\) values <0.01. These correlations were essentially similar across the European regions and individual countries (data not shown).

Table 2 shows concentrations of B-vitamins and tHcy according to relevant demographic and lifestyle factors. Women had higher concentrations of vitamins B\(_{2}\) and B\(_{12}\) compared with men, whereas vitamin B\(_{6}\) and tHcy were higher in men. Furthermore, concentrations of vitamin B\(_{12}\), folate and tHcy were higher, whereas vitamin B\(_{12}\) was lower, in individuals older than 60 years compared with younger participants. Concentrations of all vitamins were lower among smokers compared with ex- and never smokers, whereas tHcy was lowest in never smokers. Those consuming ≥30 g alcohol/d had lower vitamin B\(_{2}\), B\(_{12}\) and folate concentrations, but higher vitamin B\(_{6}\) and tHcy concentrations, compared with...
abstainers and very light or occasional consumers of alcohol. Furthermore, plasma folate concentrations were lower among those with the MTHFR 677TT genotype compared with the CC and CT genotypes, whereas tHcy concentrations were higher in the MTHFR 677TT genotype. Concentrations of B-vitamins according to these demographic and lifestyle variables were similar within each region (data not shown).

Finally, concentrations of vitamin B12 were lower, whereas concentrations of vitamins B2, B6, and tHcy were higher among those with fasting blood samples.

**Patterns of B-vitamins, amino acids and related nutrients in Europe**

We investigated patterns across three European regions (North: Sweden and Denmark; Central: France, United Kingdom, the Netherlands and Germany; South: Italy, Spain and Greece). Sex-specific standardised median (5th–95th percentile) concentrations (Table 3) showed that folate concentrations were lowest in Northern Europe in both men (10·4 (4·82–24·2) nmol/l) and women (10·7 (4·73–51·5) nmol/l) and highest concentrations were seen in Central Europe in both men (14·6 (6·40–41·8) nmol/l) and women (13·9 (6·05–44·8) nmol/l). However, the geographic pattern in tHcy concentrations – an inverse marker of folate and vitamin B12 status – did not mirror patterns of folate concentrations, and tHcy concentrations were lowest in Northern Europe. Vitamin B12 status was generally better in Northern Europe among men and women, as reflected by higher vitamin B12 and lower MMA concentrations, but did not show a clear north–south gradient. Highest vitamin B12 concentrations were observed in men (22·2 (11·1–85·0) nmol/l) and women (26·0 (12·5–69·5) nmol/l) in the North, with decreasing concentrations from the north to south (P trend < 0·001 in both sexes). Likewise, we observed that vitamin B6 concentrations were highest in Northern European women (74·4 (33·8–528) nmol/l) and decreased from the north to south (P trend < 0·001), whereas vitamin B6 concentrations in men were highest in Central Europe (77·3 (41·8–207) nmol/l) (Table 3). In men, standardised median concentrations of the amino acids sarcosine, serine and glycine were lowest in Northern Europe, and showed increasing concentrations towards Southern Europe (P trend < 0·01 for all). No such clear patterns in amino acid concentrations were observed in women. Furthermore, Southern European men had the highest concentrations of the nutrients choline and betaine, with a significant north–south gradient for both nutrients, whereas these patterns were not observed for women (Table 3). After further adjustment for season of blood collection, smoking and alcohol intake, the standardised medians remained essentially the same (data not shown).

We also compared relative differences in B-vitamin concentrations between regions at the 0·025, 0·05, 0·1, 0·25, 0·5, 0·75, 0·9, 0·95 and 0·975 percentiles of the B-vitamin distributions (Fig. 1). Relative to Southern Europe, folate concentrations in Central and the Northern Europe showed a shift to higher levels of the upper part of the distribution (for Central Europe) and a shift to lower levels of the lower part of the distribution (for Northern Europe). Differences in tHcy
Table 2. Plasma concentrations of vitamins B₂, B₆, B₁₂ and folate by demography, lifestyle and methylenetetrahydrofolate reductase (MTHFR)* genotype (Medians and 5th–95th percentiles)

<table>
<thead>
<tr>
<th></th>
<th>Folate (nmol/l)</th>
<th>Vitamin B₁₂ (pmol/l)</th>
<th>Vitamin B₂ (nmol/l)†</th>
<th>Vitamin B₆ (nmol/l)‡</th>
<th>tHcy (µmol/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>5th–95th percentiles</td>
<td>Median</td>
<td>5th–95th percentiles</td>
<td>Median</td>
</tr>
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<td>Sex</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>Male (n 2889)</td>
<td>12·6</td>
<td>5·44–34·5</td>
<td>297</td>
<td>161–523</td>
<td>18·9</td>
</tr>
<tr>
<td>Female (n 2557)</td>
<td>12·7</td>
<td>5·66–38·6</td>
<td>324</td>
<td>174–589</td>
<td>21·6</td>
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<tr>
<td>P for difference§</td>
<td>0·046</td>
<td>&lt;0·001</td>
<td>&lt;0·001</td>
<td>&lt;0·001</td>
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<td>Age (years)</td>
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<tr>
<td>&lt; 60 (n 3005)</td>
<td>12·2</td>
<td>5·58–33·3</td>
<td>316</td>
<td>175–563</td>
<td>19·8</td>
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<tr>
<td>&gt; 60 (n 2441)</td>
<td>13·0</td>
<td>5·61–39·1</td>
<td>298</td>
<td>157–550</td>
<td>20·7</td>
</tr>
<tr>
<td>P for difference§</td>
<td>&lt;0·001</td>
<td>&lt;0·001</td>
<td>0·014</td>
<td>0·126</td>
<td>&lt;0·001</td>
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<td>Smoking</td>
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<tr>
<td>Never (n 2313)</td>
<td>13·2</td>
<td>5·98–38·4</td>
<td>314</td>
<td>169–589</td>
<td>21·2</td>
</tr>
<tr>
<td>Ex (n 1867)</td>
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<td>6·01–37·4</td>
<td>305</td>
<td>162–533</td>
<td>20·8</td>
</tr>
<tr>
<td>Current (n 1196)</td>
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<td>4·66–30·7</td>
<td>304</td>
<td>160–539</td>
<td>17·8</td>
</tr>
<tr>
<td>P for trend**</td>
<td>&lt;0·001</td>
<td>0·002</td>
<td>&lt;0·001</td>
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<td>&lt;0·001</td>
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<tr>
<td>Alcohol§</td>
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</tr>
<tr>
<td>Abstainer (n 774)</td>
<td>13·3</td>
<td>5·65–39·0</td>
<td>315</td>
<td>160–614</td>
<td>20·3</td>
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<tr>
<td>0·1–4·9 g/d (n 1544)</td>
<td>12·1</td>
<td>5·31–37·1</td>
<td>318</td>
<td>168–563</td>
<td>21·0</td>
</tr>
<tr>
<td>4·9–30 g/d (n 2271)</td>
<td>12·7</td>
<td>5·66–34·7</td>
<td>304</td>
<td>165–549</td>
<td>20·5</td>
</tr>
<tr>
<td>≥30 g/d (n 835)</td>
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<td>5·89–35·5</td>
<td>300</td>
<td>164–518</td>
<td>19·0</td>
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<tr>
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<td>&lt;0·001</td>
<td>0·021</td>
<td>&lt;0·001</td>
<td>&lt;0·001</td>
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<tr>
<td>MTHFR 677*†</td>
<td></td>
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<tr>
<td>CC (n 1999)</td>
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<td>5·93–36·3</td>
<td>304</td>
<td>167–530</td>
<td>19·8</td>
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<td>CT (n 2152)</td>
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<td>5·59–34·2</td>
<td>306</td>
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<td>TT (n 631)</td>
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<td>5·02–37·2</td>
<td>298</td>
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<td>19·2</td>
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<tr>
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<td>Fasting (n 2333)</td>
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<td>5·63–37·6</td>
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<tr>
<td>Non-fasting (n 2572)</td>
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<td>316</td>
<td>167–587</td>
<td>19·1</td>
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<tr>
<td>Unknown (n 541)</td>
<td>11·0</td>
<td>5·05–40·4</td>
<td>314</td>
<td>177–549</td>
<td>24·2</td>
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<tr>
<td>P for difference§</td>
<td>0·059</td>
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<td>&lt;0·001</td>
<td>&lt;0·001</td>
<td>&lt;0·001</td>
</tr>
</tbody>
</table>

* Not measured in controls belonging to the pancreatic cancer study.
† Vitamin B₂: riboflavin + FMN.
‡ Vitamin B₆: pyridoxal-5’-phosphate + pyridoxal + 4-pyridoxic acid.
§ P for difference by Mann–Whitney U, unknown prandial status excluded from statistical test.
|| P for trend by Wald test.
|*| Data on alcohol intake and MTHFR 677C→T genotype data were available for 99·6 % (twenty-two missing) and 87·8 % (664 missing), respectively.

†Hcy, total homocysteine.
Table 3. Standardised plasma concentrations and trends across European regions* of B-vitamins and related metabolites (Medians and 5th–95th percentiles)

<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All men (n 2889)</td>
<td>All (n 2557)</td>
</tr>
<tr>
<td></td>
<td>North (n 666)</td>
<td>North (n 556)</td>
</tr>
<tr>
<td></td>
<td>Central (n 1204)</td>
<td>Central (n 1295)</td>
</tr>
<tr>
<td></td>
<td>South (n 1019)</td>
<td>South (n 706)</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>Median</td>
</tr>
<tr>
<td></td>
<td>5th–95th percentiles</td>
<td>5th–95th percentiles</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>Median</td>
</tr>
<tr>
<td></td>
<td>5th–95th percentiles</td>
<td>5th–95th percentiles</td>
</tr>
<tr>
<td>Vitamins</td>
<td></td>
<td>P_trend†</td>
</tr>
<tr>
<td>Folate (nmol/l)</td>
<td>12·7 5·63–34·8</td>
<td>13·0 5·72–39·0</td>
</tr>
<tr>
<td>B12 (pmol/l)</td>
<td>298 164–509</td>
<td>326 177–571</td>
</tr>
<tr>
<td>B2 (nmol/l)‡</td>
<td>19·1 9·59–71·2</td>
<td>21·8 10·9–76·5</td>
</tr>
<tr>
<td>B6 (nmol/l)§</td>
<td>71·2 36·5–180</td>
<td>65·6 33·7–292</td>
</tr>
<tr>
<td>Amino acids (μmol/l)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>tHcy</td>
<td>11·1 7·3–19·4</td>
<td>9·66 6·51–17·3</td>
</tr>
<tr>
<td>Cys</td>
<td>273 228–328</td>
<td>262 219–322</td>
</tr>
<tr>
<td>Met</td>
<td>26·6 18·2–39·6</td>
<td>23·9 17·0–36·3</td>
</tr>
<tr>
<td>Serk</td>
<td>133 91·4–188</td>
<td>143 95·8–206</td>
</tr>
<tr>
<td>Glyk</td>
<td>256 182–371</td>
<td>293 190–507</td>
</tr>
<tr>
<td>Sar</td>
<td>1·60 0·98–2·89</td>
<td>1·30 0·81–2·11</td>
</tr>
<tr>
<td>Nutrients or</td>
<td></td>
<td></td>
</tr>
<tr>
<td>intermediates (μmol/l)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MMA</td>
<td>0·18 0·12–0·36</td>
<td>0·17 0·11–0·34</td>
</tr>
<tr>
<td>Choline†</td>
<td>9·76 6·57–15·1</td>
<td>9·17 6·19–14·5</td>
</tr>
<tr>
<td>Betaine†</td>
<td>35·9 23·1–58·2</td>
<td>29·2 16·8–48·1</td>
</tr>
<tr>
<td>DMG†</td>
<td>3·72 2·45–6·05</td>
<td>3·24 2·10–5·42</td>
</tr>
<tr>
<td>Cystathionine</td>
<td>0·18 0·09–0·46</td>
<td>0·16 0·08–0·42</td>
</tr>
</tbody>
</table>

† Vitamin B2: riboflavin + FMN not measured in controls matched to lung cancer.
‡ Vitamin B2: riboflavin + FMN not measured in controls matched to lung cancer.
§ Not measured in controls matched to gastric and colorectal cancer.
¶ Not measured in controls matched to lung and pancreas cancer.

tHcy, total homocysteine; MMA, methylmalonic acid; DMG, dimethylglycine.
* North: Sweden and Denmark; Central: France, United Kingdom, the Netherlands and Germany; South: Italy, Spain and Greece.
† By Quantile regression, Wald test.

References to measured metabolites:
- tHcy, total homocysteine.
- MMA, methylmalonic acid.
- DMG, dimethylglycine.
- B12, vitamin B12.
- B6, vitamin B6.

Table 3. Standardised plasma concentrations and trends across European regions* of B-vitamins and related metabolites (Medians and 5th–95th percentiles)
concentrations were small. The profiles for markers of vitamin B12 status were complementary to each other, with the lowest vitamin B12 and highest MMA concentrations in Central Europe. The relative regional differences in vitamin B2 concentrations over the whole distribution range were symmetrical with higher levels for Central and the Northern Europe. There were regional differences in vitamin B6 concentrations, with highest levels in Central and the Northern Europe. The distribution curve was asymmetrical and showed most pronounced differences at higher concentrations.

Analyses of the proportion of individuals with deficient B-vitamin status, as based on the 2.5th percentile distribution of the total study population, revealed that deficiencies of vitamin B2 (6.2% with concentrations <7.9 nmol/l) and vitamin B6 (4.5% with concentrations <28.9 nmol/l) were most prevalent in Southern European countries, whereas vitamin B12 and folate deficiency were more frequently observed in Central (2.9% with concentrations <140 pmol/l) and Northern Europe (4.6% with concentrations <4.6 nmol/l), respectively (data not shown).

Distribution of folate according to methylenetetrahydrofolate reductase 677C → T genotype

There was an increasing north–south gradient for the number of T-alleles of the MTHFR 677C → T genotype (Table 1). We investigated the distribution of folate and tHcy according to the MTHFR 677C → T genotype across regions by quantile regression (Table 4 and Fig. S1, available online). In the total study population and in each region, there was a trend towards lower folate and higher tHcy concentrations according to the number of T-alleles (Table 4). Further, the distribution was asymmetric, with the largest differences in the lower quantiles of folate and the highest quantiles in tHcy. The asymmetric profile and differences were most pronounced in Southern Europe (Fig. S1, available online). Thus, the MTHFR 677TT genotype was associated with an increased prevalence of subjects with low folate and high tHcy, suggesting impaired folate status, and exerted the largest differences on distribution of these indices in populations with the highest MTHFR 677 T allele frequency.

Table 4. Plasma folate and total homocysteine (tHcy) concentrations according to the methylenetetrahydrofolate reductase (MTHFR) 677C → T genotype across European regions* (Medians and 5th–95th percentiles)

<table>
<thead>
<tr>
<th></th>
<th>North (n 1221)</th>
<th>Central (n 1221)</th>
<th>South (n 935)</th>
<th>P for difference†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median</td>
<td>5th–95th percentiles</td>
<td>Median</td>
<td>5th–95th percentiles</td>
</tr>
<tr>
<td>MTHFR 677</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma folate concentrations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT</td>
<td>10.0</td>
<td>4.24–26.5</td>
<td>12.6</td>
<td>5.95–36.5</td>
</tr>
<tr>
<td>TT</td>
<td>9.02</td>
<td>4.09–23.5</td>
<td>11.4</td>
<td>4.96–45.7</td>
</tr>
<tr>
<td>Plasma tHcy concentrations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CT</td>
<td>9.76</td>
<td>6.51–18.0</td>
<td>10.0</td>
<td>6.75–15.6</td>
</tr>
<tr>
<td>TT</td>
<td>10.6</td>
<td>6.62–20.4</td>
<td>10.7</td>
<td>6.73–21.0</td>
</tr>
</tbody>
</table>

*North: Sweden and Denmark; Central: France, United Kingdom, the Netherlands and Germany; South: Italy, Spain and Greece.
†P for difference by Kruskal–Wallis test.
Discussion

Principal findings

The present study is the largest to date to investigate geographical patterns in blood concentrations of B-vitamins, amino acids and other metabolites related to one-carbon metabolism. Folate concentrations were lowest in Northern European countries, with increasing concentrations from north to south in men. Vitamins B<sub>2</sub> and B<sub>6</sub> concentrations were highest in Northern European countries and showed a clear decreasing north–south gradient in both men and women. Concentrations of tHcy, sarcosine, serine and glycine in men were lowest in Northern Europe, and increased towards Southern Europe. The highest concentrations of the nutrients choline and betaine were observed in Southern Europe, but there was no significant north–south gradient for choline in men.

B-vitamin status

Food patterns, traditions of vitamin supplementation and lifestyle factors differ greatly across European regions. Compared with the overall EPIC study population, the dietary pattern of Italy and Greece is characterised by a higher consumption of plant foods – the main source of folate – and a lower consumption of animal – the main source of vitamin B<sub>12</sub> – and processed foods. Diets in France and Spain contain relatively high amounts of plant foods and animal products, whereas the UK general population has a relatively high consumption of tea, sauces, cakes, soft drinks, margarine and butter. Finally, the diet in the Nordic countries, The Netherlands, Germany and the UK general population is relatively high in potatoes and animal, processed and sweetened/refined foods<sup>[44,45]</sup>.

A lower intake of fruits and vegetables in Northern Europe may explain the tendency towards lower folate concentrations in the Northern region, and is in line with the previously reported lower folate intake<sup>[20,23]</sup> and plasma levels<sup>[22]</sup> in Northern countries. The higher plasma vitamin B<sub>12</sub> concentrations in Northern Europe agree with higher vitamin B<sub>12</sub> intake in Northern countries<sup>[46]</sup> and probably reflect a higher meat intake in this region<sup>[49]</sup>. Lower vitamin B<sub>2</sub> concentrations observed in Southern countries could be partially explained by a lower consumption of dairy products<sup>[47]</sup>. These findings are in line with results from the SENECA study showing a higher consumption of dairy products in Northern countries compared with Southern countries<sup>[48]</sup>, although the EPIC population had higher dairy intakes in Southern countries<sup>[47]</sup>, as well as higher intakes of vegetables, fruits and cereals, which are also sources of vitamin B<sub>2</sub>.<sup>[49]</sup>

Vitamin B<sub>6</sub> concentrations were lower in Southern countries compared with Northern countries, and differences between regions became larger at the higher end of the vitamin B<sub>6</sub> distribution, where the concentrations are similar to concentrations obtained by vitamin B<sub>6</sub> supplements.<sup>[50,51]</sup>

A subsample of the EPIC population revealed a north–south gradient in vitamin supplement use, with higher consumption in Northern European countries than in Southern European countries, and higher consumption for women than for men<sup>[52]</sup>, which could also partially explain the higher concentrations observed for vitamins B<sub>2</sub>, B<sub>6</sub> and B<sub>12</sub>, but not for folate in the Northern region.

Mandatory folic acid fortification has not been implemented in Western European countries. However, national policies on voluntary folic acid fortification vary considerably<sup>[53]</sup>, which may also affect folate status in individuals who do not use supplements<sup>[54]</sup>. In addition to higher folate status, mandatory<sup>[55]</sup> or voluntary food folic acid fortification<sup>[54]</sup> also influences the concentrations of other B-vitamins, tHcy and nutrients involved in one-carbon metabolism<sup>[56]</sup>. However, it is unclear to what extent any voluntary fortification might have affected the between-region differences in the present study.

One study observed a lower folate intake in Southern European countries in the summer compared with Northern countries<sup>[23]</sup>. This may be explained by the fact that green leafy vegetables, one of the major dietary sources of folate in those countries, are broadly known as an early-spring or late autumn crop<sup>[23]</sup>. Adjustment for season of blood collection did not affect the trends observed in the present study. Smoking behaviour<sup>[11]</sup> and alcohol consumption<sup>[13]</sup> are known lifestyle factors that affect B-vitamin status. Even though there were differences in smoking behaviour and alcohol consumption across regions, additional adjustment for these lifestyle factors did not materially alter the estimated patterns across regions.

Amino acids and other nutrients

Folate-dependent one-carbon metabolism is closely linked to pathways involving amino acids like homocysteine, methionine, serine and glycine, and donors of one-carbon units such as choline, betaine and related methylamines<sup>[3]</sup>. Therefore, it is important to consider not only B-vitamins, but also amino acids, and other nutrients and metabolites in epidemiological studies on one-carbon metabolism. Patterns of plasma concentrations of the amino acids tHcy, methionine, sarcosine, serine and glycine were consistent, with the lowest concentrations in Northern Europe and increasing concentrations towards Southern Europe in men. Likewise, men in Southern Europe had the highest concentrations of the nutrients choline and betaine, whereas in women, betaine and choline concentrations were highest in Southern and the Central Europe, respectively. The high choline concentrations are likely to be attributed to high egg consumption<sup>[50]</sup>, which has been reported to be highest in Spain<sup>[57]</sup>.

Methylenetetrahydrofolate reductase 677C → T genotype and folate status

Prevalence of the MTHFR 677TT genotype in white populations in Europe, North America and Australia varies from 8 to 20%, and a trend of increasing frequency of the TT genotype has been observed from north to south Europe<sup>[58]</sup>, which agrees with the present study. The TT variant, which was most prevalent in Southern Europe, was associated with lower folate and higher tHcy concentrations, as has previously been shown<sup>[59]</sup>. Folate and tHcy are the metabolites that are most strongly
influenced by MTHFR genotype\textsuperscript{(10)}. Although one would thereby expect lower folate status in the South as well, we observed that folate concentrations were higher in the South, suggesting that dietary factors are stronger determinants for folate status than this specific genetic factor.

Limitations and strengths

The EPIC study investigates the relation of diet and lifestyle with cancer incidence, and was as such not designed to be representative of the general European population. The study cohort comprised individuals recruited from the general population, blood donors (Spain and Italy), teachers and school workers (France), a health-conscious population (UK) and women participating in a breast cancer screening programme (The Netherlands and Italy)\textsuperscript{(23)}. The present study population may therefore reflect a more health-conscious part of the European population. The patterns observed may consequently have been under- or overestimated as a result of potential selection bias. An important strength of the present study is the large sample size of individuals recruited from several Western European countries. Nevertheless, the present study cannot provide any estimates of potential differences in disease risk profiles across the European regions as we lack data on disease status or use of medication that may affect metabolite concentrations. Furthermore, the impact of alcohol consumption on the observed patterns could not be investigated in further detail as we did not have data specifically on the consumption of beer, wine or spirits. Finally, it is known that menopausal status affects choline concentrations\textsuperscript{(60)}. However, the present study lacked statistical power to investigate whether postmenopausal status affected choline concentrations across the European regions.

A standardised protocol for the collection and storage of blood was used in the majority of participating study centres; all blood samples were collected in citrate plasma and all biochemical analyses were performed in one laboratory. This reduced pre-analytical variability due to differences in sample handling and eliminated inter-assay variations. Recently, the same laboratory investigated the stability of metabolites related to one-carbon metabolism at room temperature and during long-term storage\textsuperscript{(26)}. The results of that study underscore the importance of adequate sample handling and storage in epidemiological and clinical studies\textsuperscript{(26)}. Folate, species of vitamins B\textsubscript{2} and B\textsubscript{6}, and choline appear to be unstable during storage\textsuperscript{(26)}. However, the sum of riboflavin and FMN and the sum of pyridoxal-5'-phosphate, PL and 4-pyridoxic acid are stable, and we therefore presented the sum of these species as measures of vitamins B\textsubscript{2} and B\textsubscript{6} status in the present investigation. In addition, concentrations of choline, but not betaine, increase with increasing storage time\textsuperscript{(26)}. Therefore, higher concentrations of both choline and betaine observed in Central European countries are more likely explained by a higher dietary intake of choline than by pre-analytical errors. The observed correlations between metabolites were essentially the same when calculated within countries, regions or the total study population, observations that support data integrity.

Conclusions

The present study covers a large geographical area in Europe, and presents a comprehensive spectrum of B-vitamins, amino acids and other nutrients involved in one-carbon metabolism. The study reveals clear decreasing north–south gradients of vitamins B\textsubscript{2} and B\textsubscript{6}, and increasing gradients of folate and the majority of amino acids included in the present study. These differences may reflect distinct dietary and lifestyle patterns between regions, and may be relevant for the study of regional differences in chronic disease incidence in Western Europe.

Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S0007114512004990

Acknowledgements

The work was supported by the European Commission: Public Health and Consumer Protection Directorate 1993–2004; Research Directorate-General 2005; Ligue contre le Cancer (France); Société 3M (France); Mutuelle Générale de l’Education Nationale; Institut National de la Santé et de la Recherche Médicale (INSERM); German Cancer Aid; German Cancer Research Center (DKFZ); German Federal Ministry of Education and Research; Danish Cancer Society; Health Research Fund (FIS) of the Spanish Ministry of Health (RTICCD RD06/0020), the participating regional governments from Asturias, Andalucia, Murcia, Navarra and Vasco Country and the Catalan Institute of Oncology of Spain; Cancer Research UK; Medical Research Council, UK; Stroke Association, UK; British Heart Foundation; Department of Health, UK; Food Standards Agency, UK; Wellcome Trust, UK; the Hellenic Health Foundation and the Stavros Niarchos Foundation, Greece; Italian Association for Research on Cancer (AIRC); Compagnia San Paolo, Italy; Dutch Ministry of Public Health, Welfare and Sports; Dutch Ministry of Health; Dutch Prevention Funds; LK Research Funds; Dutch ZON (Zorg Onderzoek Nederland); World Cancer Research Fund (WCRF); Swedish Cancer Society; Swedish Scientific Council; Regional Government of Skåne, Sweden; Norwegian Cancer Society; Foundation to promote research into functional vitamin B\textsubscript{12}-deficiency, Norway. The authors’ responsibilities were as follows: S. J. P. M. E., R. M. N., Ø. M., S. H., N. IJ., K. M., A. F., A. U., P. M. U., P. B., M. J., B. B. d. M., P. V., S.-C. C. and S. E. V. constituted the writing group, conducted the statistical analysis and prepared the manuscript; all other authors contributed to and/or provided comments and suggestions on the intermediate and final manuscripts. All authors read and approved the final manuscript. None of the authors reported a personal or financial conflict of interest.
References