Single oral doses of $^{13}$C forms of pteroylmonoglutamic acid and 5-formyltetrahydrofolic acid elicit differences in short-term kinetics of labelled and unlabelled folates in plasma: potential problems in interpretation of folate bioavailability studies

A. J. A. Wright¹, P. M. Finglas¹*, J. R. Dainty¹, D. J. Hart¹, C. A. Wolfe¹, S. Southon¹ and J. F. Gregory²

¹Nutrition Department, Institute of Food Research, Norwich Research Park, Colney, Norwich NR4 7UA, UK
²Food Science and Human Nutrition Department, PO Box 110370, University of Florida, Gainesville, FL 32611-0370, USA

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Single $^{13}$C₆-labelled doses of pteroylmonoglutamic acid (PteGlu; 634 nmol) or 5-formyltetrahydrofolic acid (431–569 nmol) were given to fasted adult volunteers, and the rise in total and $^{13}$C-labelled plasma 5-methyltetrahydrofolic acid metabolite monitored over 8 h by HPLC and liquid chromatography–MS. The dose-adjusted area under the curve (AUC) for total (labelled plus unlabelled) plasma 5-methyltetrahydrofolic acid following a 5-formyltetrahydrofolic acid test dose was 155 % that obtained following a PteGlu test dose. Surprisingly, an average 60 and 40 % of the total plasma 5-methyltetrahydrofolic acid response to $[^{13}$C₆]PteGlu and $[^{13}$C₆]5-formyltetrahydrofolic acid, respectively, was unlabelled; an observation never before reported. Short-term kinetics of plasma $[^{13}$C₆]5-methyltetrahydrofolic acid showed a slower initial rate of increase in plasma concentration and longer time to peak following an oral dose of $[^{13}$C₆]PteGlu compared with that for an oral dose of $[^{13}$C₆]5-formyltetrahydrofolic acid, while the $[^{13}$C₆]5-methyltetrahydrofolic acid AUC for $[^{13}$C₆]5-formyltetrahydrofolic acid was 221 % that for $[^{13}$C₆]PteGlu. These data indicate that PteGlu and 5-formyltetrahydrofolic acid, which are thought to be well absorbed (about 90 %) at physiological doses, exhibit dramatically different rates and patterns of plasma response. A limitation in the rate of reduction of PteGlu before methylation could result in slower mucosal transfer of $[^{13}$C₆]5-methyltetrahydrofolic acid derived from $[^{13}$C₆]PteGlu into the plasma. This, when coupled with an observed similar plasma clearance rate for $[^{13}$C₆]5-methyltetrahydrofolic acid metabolite derived from either folate test dose, would yield a comparatively smaller AUC. These findings suggest potential problems in interpretation of absorption studies using unlabelled or labelled folates where the rate of increase, the maximum increase, or the AUC, of plasma folate is employed for test foods (mainly reduced folates) v. a ‘reference dose’ of PteGlu.


Folate is a generic term for B-group vitamins found widely in foodstuffs, mainly reduced methyl and formyl folates (Perry, 1971), that have nutritional properties and chemical structures similar to those of pteroylmonoglutamic acid (PteGlu) (Scott & Weir, 1976). PteGlu is the synthetic form of the vitamin that is used extensively for food fortification purposes and supplements, but which does not occur naturally in significant amounts. Folates are crucial for methionine and nucleotide biosynthesis (Shane, 1995). Periconceptual supplementation of women with PteGlu has been shown to significantly reduce the incidence and recurrence of neural tube defects, such as spina bifida (Anonymous, 1991; Czeizel & Dudas, 1992). Marginal folate deficiency is also associated with elevated plasma homocysteine, an emerging risk factor for vascular diseases (Bousey et al. 1995), epigenetic factors such as cytosine-phosphate-guanosine dinucleotide methylation-associated transcription factor-binding (Nephew & Huang, 2003) and uracil-induced genomic instability (Blount et al. 1997). Either manipulation of the diet or fortification of food with physiological levels of PteGlu may be expected to reduce the prevalence of these folate-related diseases. However, the bioavailability of different folate vitamers is not well understood. Is folate status increased best by the intake of folate supplements, fortified foods or natural food folates? Is optimal folate status easily achievable in countries that do not permit the PteGlu fortification of foodstuffs? Methods for the assessment of folate bioavailability in human subjects include the comparison of the serum or

Abbreviations: AUC, area under the curve; 5-CH₃H₄PteGlu, 5-methyltetrahydrofolic acid; 5-CHOH₄PteGlu, 5-formyltetrahydrofolic acid; 5MTHF, 5-methyltetrahydrofolic acid; PteGlu, pteroylmonoglutamic acid.

* Corresponding author: P. M. Finglas, fax +44 1603 507723, email paul.finglas@bbsrc.ac.uk

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plasma response to a single oral dose relative to that of a PteGlu reference dose (Gregory, 1997, 2001). This may entail either measurement of the rate of increase, or the maximum increase, in plasma folate concentration over 2 to 3 h (Perry & Chanarin, 1970, 1972; Brown et al. 1973; Lucock et al. 1989; Bower et al. 1993; Kelly et al. 1997), or measurement of the rise in plasma folate concentration (the area under the curve (AUC) of the increase in plasma folate concentration above fasting baseline level) over 6 h or more (Markkanen, 1968, 6 h AUC; Bailey et al. 1988, 8 h AUC; Fenech et al. 1999, 7 h AUC; Prinz-Langenhohl et al. 1999, 10 h AUC). In respect of methodological aspects in vitamin bioavailability testing, the AUC is accepted as a valuable indicator of bioavailability provided the post-dosing plasma measurement test period is long enough to capture > 80 % of the whole AUC (Pietrzik et al. 1990).

Because of the potential benefits of specificity and sensitivity, it is increasingly common to study the absorption and metabolism of folates in human subjects by using stable-isotope-labelled folates (Wolfe et al. 2001). Our group has used such an approach to assess the relative absorption of two different folate vitamers; PteGlu and 5-formyltetrahydrofolic acid (5-CHOH4PteGlu). This way, folate can be followed and differentiated from the natural store of folate already present in the body. Thus, more accurate estimates of ‘relative absorption’ should be able to be calculated as a result.

During the course of these studies it became apparent that there are a number of problems in interpreting comparative folate absorption based on short-term plasma folate responses, even when folate test doses are labelled. The present paper presents the evidence for this statement, which emerged in a human volunteer study. Human plasma 5-methyltetrahydrofolic acid (5-CH3H4PteGlu) AUC excision profiles were followed over a period of 8 h following ingestion of single oral physiological doses of 13C6-labelled PteGlu or (6S-)-13C6-labelled 5-CHOH4PteGlu. Folate-binding affinity columns were used to isolate extracted plasma folate and, following HPLC analysis of folate concentrations, a newly developed liquid chromatography–MS analytical method was used to determine the proportions of 13C6-labelled and unlabelled 5-CH3H4PteGlu (Hart et al. 2002).

Materials and methods

Materials

Purified [2H2]PteGlu was synthesised using a previously published procedure (Gregory, 1990), stored frozen at −18°C, and used as the internal standard. Proton NMR, HPLC and mass spectrometric results gave a purity of > 99 % and an isotopic enrichment of > 95 %. Purified [13C6]PteGlu with an isotope enrichment of 96 % was synthesised by the method of Mauder et al. (1999), and then encapsulated in gelatin capsules (‘softgels’) and stored at +4°C (Finglas et al. 2002b). These capsules release their contents rapidly once in contact with acid stomach contents and the bioavailability of encapsulated water- and acid-soluble compounds (such as folates), as measured by plasma appearance, has been shown to be indistinguishable from oral aqueous solutions (Seager et al. 1988). Purified (6S-)-[13C6]5-CHOH4PteGlu was synthesised using a previously published enzymic–chemical procedure (Moran et al. 1986), and stored frozen, as a solid, at −18°C. The purified [13C6]5-CHOH4PteGlu was checked by HPLC analysis, u.v. spectrum and MS. The mass spectrum gave an isotopic enrichment of > 94 %. There were no detectable impurities and contaminants from the HPLC chromatogram, and u.v. spectra gave an estimated purity > 98 %.

Intermittently, as required, a batch of oral doses of [13C6]5-CHOH4PteGlu were prepared. Approximately 10 µmol solid was weighed out and dissolved in 0.5 ml NaOH solution (0.1 mol NaOH/l). High-grade water was then added to obtain a solution of about 1.2 µmol/ml. This was then dispensed, in doses of 0.5 ml (about 600 nmol), into 2.0 ml plastic screw-capped microfuge tubes. One dose was retained for spectroscopic analysis, with folate concentration being calculated after further dilution in PBS (0.1 mol/l, pH 7.0) using a molar extinction coefficient (E(mol, 10 mm)) of 37 200 (Blakley, 1969). The residual doses were temporarily stored frozen at −18°C until required, and used within 2 weeks.

Human study design

The present work forms part of an ongoing crossover, within-subject, study comparing the absorption of 13C6-labelled folate isolates or 15N-intrinsically labelled spinach folates in a group of healthy male and female adults. The study was approved by the Norwich and District Ethics Committee (Norfolk & Norwich Area Health Care Trust). After giving written consent, a 12 h fasting blood sample was taken and analysed at the haematology department of a local hospital for full-blood-count, blood glucose, erythrocyte-folate, serum B12, ura and electrolytes, and liver function tests. If all results were inside normal assay ranges, volunteers then attended test days where, following an overnight fast, a baseline (time zero) blood sample (10 ml) was taken and where they were then given a single oral dose of [13C6]PteGlu (634 nmol) or (6S-)-[13C6]5-CHOH4PteGlu (431–569 nmol). The dose of [13C6]PteGlu was administered in gelatin capsules washed down with a glass of bottled ‘still’ mineral water. The thawed dose of (6S-)-[13C6]5-CHOH4PteGlu was added to a glass of 25 ml bottled ‘still’ mineral water and then drunk by the volunteer. The glass was quickly rinsed out twice with further water, which was also drunk. A timer was started after the test doses had been completely swallowed and rinsed down. Volunteers were always allowed access to water, and were given a light lunch only after a 4 h post-dosing venous blood sample had been obtained. With few exceptions, the sub-set of volunteers reported in the present paper did not complete both 13C6-labelled PteGlu and 5-CHOH4PteGlu test days. The present paper therefore reports essentially independent results from ten volunteers (age 30.9 (SE 1.3) years; BMI 25.7 (SE 1.3) kg/m2) who had (6S-)-[13C6]5-CHOH4PteGlu as the test dose and twelve volunteers (age 31.1 (SE 1.2) years; BMI 25.4 (SE 1.3) kg/m2) who had [13C6]PteGlu as the test dose.
Blood sampling and storage
Venous blood samples (10 ml) were taken by cannula at time zero and at eleven further time points over an 8 h period following each test dose; 0, 0·5, 1, 1·5, 2, 2·5, 3, 3·5, 4, 5, 6 and 8 h. Blood samples were transferred immediately into tubes containing K₂EDTA (Sarstedt Ltd, Beaumont Leys, Leic., UK) and mixed gently. Samples were centrifuged (1500g, 10 min), plasma removed and frozen immediately over solid CO₂, and then stored at −30°C until analysis.

Sample preparation, folate extraction and analysis
Following storage, plasma samples were mixed thoroughly and 5 ml transferred into 50 ml screw-top glass centrifuge tubes. Extraction buffer (20 ml, 0·1 m-K₂HPO₄, pH 7·0; containing 0·05 m-sodium ascorbate and 0·01 m-mercaptoethanol as antioxidant) and an internal standard (0·1 ml [²H₂]PteGlu; 2 µg/ml) were added. The tubes were then flushed with N₂, capped, and the sample mixed thoroughly before being placed into a boiling water bath for 10 min for proteins to precipitate. The samples were cooled over ice, precipitates agitated, then centrifuged for 10 min (1000 g). The supernatant fraction was removed and stored in a clean tube. Extraction buffer (15 ml) was added to the pellet and thoroughly mixed. The sample was re-centrifuged and the wash supernatant fraction removed and combined with the first supernatant fraction. All folate from each extracted plasma sample was purified on an affinity column using folate-binding protein and eluted with HCl (0·1 mol/l) into a 5 ml volumetric flask containing ascorbic acid solid (10 mg), mixed thoroughly, and transferred in three roughly equal portions to microfuge tubes (Hart et al. 2002). These folate isolates were temporally stored in liquid N₂ (with no loss of potentially labile 5-CH₃H₄PteGlu, PteGlu, even after several months) and subsequently analysed, utilising a cooled (4°C) autoinjector, in negative ion mode by liquid chromatography–MS as previously described (Hart et al. 2002). Selected ion monitoring was conducted on the [M-H]⁻ ion: m/z 458 for analysing 5-CH₃H₄PteGlu; m/z 464 [M + 6-H]⁻ to determine 5-CH₃H₄PteGlu derived from the label dose; m/z 444 for analysing 5-CHOH₄PteGlu internal standard; m/z 446 and 478 to confirm there was no evidence of unmetabolised labelled PteGlu or 5-CHOH₄PteGlu originating from the oral test doses. Total plasma 5-CH₃H₄PteGlu concentrations were analysed (100 µl injection) by HPLC utilising a cooled (7°C) autoinjector (with no loss of potentially labile 5-CH₃H₄PteGlu, even after 30 h). Chromatographic separation was on a 250 mm × 4·6 mm internal diameter column packed with LiChrospher 100 RP C₁₈ (Merck Ltd, Poole, Dorset, UK), performed isocratically at 1·0 ml/min with a mobile phase consisting of phosphoric acid (0·05 mol/l)–acetonitrile (9·1: v/v) with fluorescence detection for 5-CH₃H₄PteGlu (excitation at 292 nm and emission at 356 nm) and u.v. absorbance (288 nm) for both PteGlu and 5-CHOH₄PteGlu. HPLC quantification was against external standards. Stock folate solutions were made up in borate buffer (0·1 mol/l, pH 9·3) containing 0·4% (v/v) mercaptoethanol, and samples were further diluted in phosphate buffer (0·1 mol/l, pH 7·0; van den Berg et al. 1994) before true folate concentrations were established using appropriate molar extinction coefficients (Blakley, 1969).

When required, sub-samples of stock solutions (that had been stored in liquid N₂) were thawed and diluted to suitable concentrations with HCl (0·1 mol HCl/l containing 2 mg/ml ascorbic acid as an antioxidant); the same matrix as used for isolated plasma samples. Plasma concentrations of unlabelled and ¹³C₆-labelled 5-CH₃H₄PteGlu were calculated using selected ion monitoring ratios (Hart et al. 2002) (see Appendix 1). Step 1 involves calculating the fraction of each source in the sample. Step 2 involves multiplying the measured total 5-CH₃H₄PteGlu concentration by the derived fraction of each source to give the actual plasma concentrations of unlabelled and ¹³C₆-labelled 5-CH₃H₄PteGlu.

Area under the curve calculations of the rise in plasma folate above initial fasting baseline concentration
The AUC was calculated using the trapezoidal method, and then adjusted to an oral dose equivalent to 600 nmol folate. For each test dose, in each volunteer, both the ‘total’ and the ‘unlabelled’ plasma 5-CH₃H₄PteGlu AUC (the AUC of the rise in plasma folate concentration) were calculated after deduction of each individual’s baseline (time zero) concentration from the concentration values obtained for each of their post-absorption time points. The ¹³C₆-labelled 5-CH₃H₄PteGlu AUC was calculated without adjustment, since there was no excess label at baseline (time zero).

Statistics
Originally, our ongoing study (of which the volunteers reported on in the present paper form a part) had a cross-over within-subject design. However, partly because of the intrusive nature of 8 h cannulations, most subjects reported here did not complete both ¹³C₆-labelled PteGlu and 5-CHOH₄PteGlu test days. Hence, for statistical purposes, the data that are reported in the present paper are treated as independent observations. For PteGlu and 5-CHOH₄PteGlu test meals, plasma total, labelled and unlabelled AUC, unlabelled:labelled ratio and total:labelled ratio were examined by the Kolmogorov–Smirnov one-sample continuous distribution test. As distributions were not significantly different from normal, each parameter for the two test doses was compared by parametric Student’s unpaired t test for: (i) total plasma 5-CH₃H₄PteGlu AUC; (ii) plasma ¹³C₆-labelled 5-CH₃H₄PteGlu AUC; (iii) plasma unlabelled 5-CH₃H₄PteGlu AUC; (iv) plasma unlabelled:labelled 5-CH₃H₄PteGlu AUC ratio; (v) plasma total:labelled 5-CH₃H₄PteGlu AUC ratio. Linear regression analysis was used to assess associations (r²) with either fasting plasma baseline folate concentration, or erythrocyte-folate concentration. It was also used, within subject, to assess association between labelled and unlabelled plasma 5-CH₃H₄PteGlu AUC response.
Results

Selected ion monitoring indicated that neither of the test doses appeared unmetabolised in the plasma as PteGlu or 5-CHOH4PteGlu.

The total plasma response to both labelled PteGlu and 5-CHOH4PteGlu test doses was significantly greater than their labelled plasma response. This indicates that there was a significant appearance of unlabelled folate in the plasma following both test folates (Fig. 1).

The labelled plasma response to PteGlu was slower, and peaked much later than the response to the 5-CHOH4PteGlu test dose ($T_{\text{max}}$ 173 (se 10) v. 41 (se 9) min respectively). $T_{\text{max}}$ is the time between the administration of the dose and the occurrence of the peak plasma concentration of labelled 5MTHF.

Table 1 shows (i) ‘total’, (ii) ‘labelled’, and (iii) ‘unlabelled’ plasma AUC responses, together with the (iv) unlabelled:labelled and total:labelled AUC ratios to the PteGlu and 5-CHOH4PteGlu test doses.

On average, the ‘total’ plasma AUC response to 5-CHOH4PteGlu was 155 % of the response to PteGlu; a significant trend for difference ($P<0·062$).

In comparison, the average plasma ‘labelled’ AUC response to 5-CHOH4PteGlu was 221 % of the response to PteGlu; a significant difference ($P<0·001$).

In contrast to the ‘total’ and ‘labelled’ response, the average plasma ‘unlabelled’ AUC response to 5-CHOH4PteGlu was the same as the response to PteGlu; no significant difference ($P=0·864$).

Plasma ‘unlabelled’ and ‘labelled’ AUC varied greatly between volunteers but an ‘unlabelled’ plasma response was always present. Notably, there was no significant association, within subject, between ‘unlabelled’ and ‘labelled’ plasma AUC responses to either PteGlu ($r^2 0·039$; $P=0·541$) or 5-CHOH4PteGlu ($r^2 0·166$; $P=0·243$) test doses.

A comparison of the plasma ‘unlabelled’:‘labelled’ AUC ratios for the two oral folate test doses indicated that the mean ratio for PteGlu (1·43) was more than double, and significantly different ($P=0·012$), than the mean ratio for 5-CHOH4PteGlu (0·61).

A comparison of the plasma ‘total’:‘labelled’ AUC ratios for the two oral folate test doses indicated that the mean ratio for PteGlu (2·27) was significantly different ($P=0·027$) from the mean ratio for 5-CHOH4PteGlu (1·47).

Table 2 shows the results of linear regression analysis between both labelled and unlabelled plasma AUC responses to PteGlu and 5-CHOH4PteGlu test doses with (a) fasting plasma and (b) erythrocyte-folate concentrations. It also shows that there was no relationship between fasting plasma and erythrocyte-folate concentrations. Neither ‘unlabelled’ nor ‘labelled’ plasma AUC responses were significantly associated ($r^2$) with volunteer fasting baseline erythrocyte-folate concentrations. Furthermore, neither the ‘unlabelled’ plasma AUC response to both test folates, nor the ‘labelled’ plasma AUC response to the 5-CHOH4PteGlu test dose, were significantly associated ($r^2$) with volunteer fasting baseline plasma concentrations. However, interestingly, there was an extremely high degree of association between the ‘labelled’ plasma AUC response to the PteGlu test dose, and volunteers’ fasting baseline plasma folate concentration ($r^2 0·880$; $P<0·001$).

Discussion

The size of the oral folate test doses used in the present study did not exceed any threshold for the reported direct appearance of unmetabolised PteGlu in the plasma (Kelly et al. 1997); consequently no evidence of unmetabolised PteGlu or 5-CHOH4PteGlu appearing in any of the analysed samples was found.

Results indicated that a significant proportion of the total plasma AUC response to an oral load of labelled PteGlu or labelled 5-CHOH4PteGlu did not originate directly from the oral test doses because it was not labelled (Fig. 1(a) and (b)). Approximately 40 % (range 7 to 64 %) of the plasma response to the dose of labelled 5-CHOH4PteGlu, and approximately 60 % (range 38 to 75 %) of the plasma response to the dose of labelled PteGlu did not

Fig. 1. (a) Plasma response to (6S-) $[^{13}C_6]$5-formyltetrahydrofolic acid (5-CHOH$_4$PteGlu). Mean values with their standard errors of total (●) and $^{13}C_6$-labelled (○) plasma 5-methyltetrahydrofolinic acid (5-CHOH$_4$PteGlu) areas under the curve (AUC) of the rise in plasma folate concentration in response to an oral test dose (n 10) of (6S-) $[^{13}C_6]$CHOH$_4$PteGlu. AUC responses are adjusted to an oral dose of 600 nmol. The unlabelled response, not of test-dose origin, is the difference between the two responses shown. (b) Plasma response to $[^{13}C_6]$pteroylmonoglutamic acid (PteGlu). Mean values with their standard errors of total (●) and $^{13}C_6$-labelled (○) plasma 5-CHOH$_4$PteGlu AUC of the rise in plasma folate concentration in response to an oral test dose (n 12) of $[^{13}C_6]$PteGlu. AUC responses are adjusted to an oral dose of 600 nmol. The unlabelled response, not of test-dose origin, is the difference between the two responses shown.
Table 1. Plasma 5-methyltetrahydrofolic acid (5-CHOH_4PteGlu) area under the curve (AUC) responses and unlabelled:labelled and total:labelled ratios in fasting healthy adult volunteers following an oral dose of either [13C_6]pteroylmonoglutamic acid (PteGlu) or (6S)-[13C_6]5-formyltetrahydrofolic acid (5-CHOH_4PteGlu) (Mean values with their standard errors)

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<tr>
<td>Total AUC</td>
<td>2437 300</td>
<td>3771 646</td>
<td><em>P</em> = 0.062 (trend)</td>
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<tr>
<td>[13C_6]-labelled AUC</td>
<td>1149 128</td>
<td>2542 187</td>
<td><em>P</em> &lt; 0.001</td>
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<tr>
<td>Unlabelled AUC</td>
<td>1497 257</td>
<td>1589 503</td>
<td><em>P</em> = 0.864 (NS)</td>
</tr>
<tr>
<td>Ratio of unlabelled:labelled</td>
<td>1.43 0.23</td>
<td>0.61 0.17</td>
<td><em>P</em> = 0.012</td>
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<tr>
<td>Ratio of total:labelled</td>
<td>2.27 0.26</td>
<td>1.47 0.20</td>
<td><em>P</em> = 0.027</td>
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* All AUC responses are adjusted to an oral dose of 600 nmol, and are over the post-dosing period from 0 to 480 min.
† Student’s unpaired t-test.

Table 2. Linear regression analysis of the association (r^2) between unlabelled or [13C_6]-labelled plasma 5-methyltetrahydrofolic acid (5-CHOH_4PteGlu) area under the curve (AUC) response in fasting healthy adult volunteers, following an oral dose of either [13C_6]pteroylmonoglutamic acid (PteGlu) or (6S)-[13C_6]5-formyltetrahydrofolic acid (5-CHOH_4PteGlu), and fasting plasma folate concentration or fasting erythrocyte-folate concentration

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<td>Fasting plasma folate</td>
<td>Fasting erythrocyte folate</td>
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<tr>
<td>Unlabelled AUC per 600 nmol dose</td>
<td>0.000 0.007</td>
<td>0.066 0.004</td>
</tr>
<tr>
<td>[13C_6]-labelled AUC per 600 nmol dose</td>
<td>0.990 (NS) 0.805 (NS)</td>
<td>0.196 (NS) 0.265 (NS)</td>
</tr>
<tr>
<td>Fasting plasma (oral dose PteGlu)</td>
<td>0.880 0.022</td>
<td>0.226 0.174</td>
</tr>
<tr>
<td>Fasting plasma (oral dose 5-CHOH_4PteGlu)</td>
<td>0.032 0.001</td>
<td>0.102 0.442</td>
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This result has not been demonstrated previously. The ‘unlabelled’ plasma AUC response cannot be as a result of metabolic cleavage and loss of label from the test folates during subsequent metabolism. The underlying parent structure of all monoglutamate folate compounds that exhibit a common vitamin activity is based on the parent structure of PteGlu (pteroyl-L-mono glutamic acid). The pteroylmonoglutamate molecule consists of an aromatic pteridine ring linked through a methylene bridge to para-aminobenzoic acid, and then to one L-glutamic acid residue. Cleavage between the pteridine ring and benzoic-acid ring (generating a pteridine residue + para-aminobenzoic acid), between the benzoic-acid ring and glutamic acid (generating pteroid acid + glutamic acid), or between both (generating a pteridine residue + para-aminobenzyl residue + glutamic acid), will result in molecules with no vitamin activity that human metabolism cannot reassemble. Hence, the classification of folates as ‘vitamins’. It is thus self-evident that the benzene ring of the earlier absorbed and substituted with a non-labelled ring without irreversible destruction of the vitamin folate molecule.

The large, and highly variable, displacement of endogenous folate is problematic in interpreting absorption studies using ‘unlabelled’ folates because the portion of plasma response due to oral v. endogenous folate cannot be determined. There was no relationship between this ‘unlabelled’ folate response and folate status. Furthermore, there does not appear to be a simple relationship between oral and endogenous response as there was no significant association, within subject, between ‘unlabelled’ and ‘labelled’ plasma AUC response to either ‘labelled’ PteGlu or ‘labelled’ 5-CHOH_4PteGlu test doses. It could be speculated that the larger variation in unlabelled plasma folate response may be due to variable absorptive epithelial cell exposure to folate intake in the day-or-so immediately preceding the test days, and a knock-on perturbation effect. The latter effect would result in the previously absorbed ‘cold’ folate being pushed out of the epithelial cells into the body-proper to generate an unlabelled folate plasma response that is completely unpredictable, and unrelated to the absorption of any labelled test dose. If unlabelled
oral doses of both PteGlu and 5-CHOH4PteGlu will only
the serosal side. It is therefore expected that physiological
substitution (methylation) of physiological doses of folate
intestine is capable of both reduction and one-carbon sub-
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The oral dose of 5-CHOH₂PteGlu induced larger 'total'
plasma AUC responses than equivalent oral doses of
PteGlu (Table 1). If the AUC of an unlabelled oral test
folate is compared with the AUC of an equivalent
unlabelled dose of PteGlu (i.e. using PteGlu as the 'refer-
ence' dose) then this would have indicated that the 'relative
bioavailability' of 5-CHOH₂PteGlu was 155 % that of
PteGlu. Similarly, the 'relative bioavailability' of
5-CHOH₂PteGlu calculated when using only the plasma
'labelled' AUC responses was 221 % that of PteGlu.
Under the conditions of the present trial in which relatively
small folate test doses (within the physiological range)
were given to fasting volunteers, one would expect that a
high proportion (approximately 90 %) of the dose would
be absorbed (Bhandari & Gregory, 1992; Clifford et al.
1998). Thus, differences in plasma kinetics and AUC as
seen in the present study are almost assuredly due to differ-
ences in rate or extent of conversion to 5-CH₃H₄PteGlu,
displacement of tissue folates, and release into the circula-
tion. These data suggest that a reduced folate such as (6S-)
5-CH₃H₄PteGlu or (6S-) 5-CHOH₂PteGlu would be a more
appropriate 'reference' dose in bioavailability studies of
natural folates, especially comparisons carried out 'within
volunteer'.

A review by Selhub et al. (1983) concluded that the intestine
is capable of both reduction and one-carbon substi-
tution (methylation) of physiological doses of folate
before absorbed folate is transported from the mucosal to
the serosal side. It is therefore expected that physiological
oral doses of both PteGlu and 5-CHOH₂PteGlu will only
result in the transfer of 5-CH₃H₄PteGlu into the hepatic
portal vein. Though an extensive hepatic uptake of
absorbed folate has been noted (Gregory, 2001), this, logi-
cally, should be the same in response to both these oral test
folates and calculation of 'relative absorption' should still
be valid. However, a comparison of labelled plasma
AUC responses indicated that the 'initial rate' and 'time to
peak' response to PteGlu test doses was slower and
longer, respectively, than that to 5-CHOH₂PteGlu test
doses (Fig. 1(a) and (b)). Arguably, a slower mucosal
transfer of labelled 5-methyltetrahydrofolic metabolite,
derived from labelled PteGlu, to the plasma (possibly due
to a limitation in the rate of initial reduction of PteGlu
to H₂PteGlu, before further reduction to H₄PteGlu,
subsequent 1-carbon addition and re-arrangement to
5-CH₃H₄PteGlu; Mathews & Huennekens, 1963) when
coupled with a similar plasma clearance rate to 5-methylte-
trahydrofolic metabolite derived from 5-CHOH₂PteGlu
would result in a comparatively smaller 'labelled' plasma
AUC.

The lack of association (Table 2), with one exception,
between labelled or unlabelled plasma AUC responses to
PteGlu or 5-CHOH₂PteGlu test doses, and either volunteer
fasting baseline plasma or erythrocyte-folate concen-
trations, indicates that plasma AUC responses cannot be
predicted using either of these criteria. The exceptional
observation of a high degree of association (r² = 0.880;
P<0.001) between the labelled plasma AUC response to
a labelled PteGlu oral test dose and volunteers’ fasting
baseline plasma folate concentration could be real, and
could eventually provide an insight into the specific meta-
bolism of PteGlu. Alternatively, the association could be
an artifact of having undertaken a total of ten statistical
comparisons (i.e. including testing of associations between
'unlabelled' and 'labelled' plasma response to both test
folates). So, without an experimental 'a priori' intention
to make such comparisons, the associations should, strictly
speaking, be left to future examination. However, since
fasting baseline plasma folate concentration is maintained
by enterohepatic recirculation (Steinberg et al. 1979), it
is too tempting to avoid the speculation that this strong
relationship suggests that absorbed PteGlu is reduced and
methylated in the liver, and not the mucosa, as has been
the accepted wisdom for at least the past two decades
(Selhub et al. 1983).

In summary, the present paper reports that after an oral
tolate test dose there is a large and unexpected concurrent
displacement of tissue 5-CH₃H₄PteGlu into the plasma.
This makes comparisons of the relative bioavailability of
unlabelled reduced folates (i.e. from test food doses), v.
unlabelled PteGlu reference doses, ambiguous. It is
also reported that there is a large difference in plasma
'labelled' response to a 'labelled' naturally occurring
reduced folate compared with 'labelled' unlabelled
PteGlu. This difference would lead to spurious conclusions
in bioavailability studies based on comparisons of oral
doses of reduced 'labelled' folate (for example, labelled
food folate) v. a 'labelled' PteGlu reference dose. It
could be speculated that this phenomenon may be due to
a slower rate of mucosal processing of PteGlu compared
with 5-CHOH₂PteGlu. This may result in a slower
transfer of 5-CH₃H₄PteGlu metabolite to the plasma,
which will, when coupled with a similar clearance rate to
that of 5-CH₃H₄PteGlu metabolite derived from oral
5-CHOH₂PteGlu, result in comparatively smaller labelled
plasma AUC. Contrary to current theory, it is suggested
that absorbed physiological doses of PteGlu mainly enter
the hepatic portal vein unmodified with immediate removal
to the liver for biotransformation, with subsequent plasma
5-CH₃H₄PteGlu AUC response being entirely a function of
enterohepatic recirculation.

Thus, neither comparison of 'total' or 'labelled' plasma
AUC responses appears to give a reliable index of 'relative
bioavailability'. It is concluded that currently held views
on the absorption, metabolism and subsequent tissue distri-
bution of folates (which suggest that the bioavailability of
oral test doses can be estimated by contrasting the plasma
response with that from an equivalent 'reference dose' of
PteGlu), need re-evaluation.

Two potential solutions to this problem are suggested.
First, an adaptation could be made to the oral and intra-
venous dual-label stable-isotope 'urinary excretion ratio'
protocol of Gregory et al. (1992), using isotopically
labelled (6S-) 5-CH₃H₄PteGlu as the intravenous dose,
rather than isotopically labelled PteGlu. This adaptation
to the method may overcome differences in the kinetics

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of urinary excretion of oral and intravenous doses that have been observed when using labelled PteGlu as the intravenous dose (Gregory et al. 1992; Rogers et al. 1997; Finglas et al. 2002b). However, this manoeuvre may eventually prove to be only a partial solution and have to be restricted to the estimation of the ‘relative absorption’ of oral doses of ‘natural’ reduced folates and not PteGlu (as either supplement or fortificant). Second, one could mathematically model plasma-labelled response data (entrance and clearance rates) using a single-compartment model with estimates for the size of pool mass and volume, and (perhaps) first-pass liver effect. The advantages of this approach may be at least to obtain an accurate estimate of ‘relative bioavailability’, if not absolute absorption. Metabolic models are currently being investigated (Finglas et al. 2002a).

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References


Rogers LM, Pfeiffer CM, Bailey LB & Gregory JF (1997) A dual-label stable-isotope protocol is suitable for determination of


Appendix 1

There are two possible sources of 13C in the 5-CH3H4PteGlu in our plasma samples: the tracer (the 13C5, labelled 5-CH3H2PteGlu; 5MTHF) and the tracee (unlabelled 5-CH3H2PteGlu). The mass spectrometer is set up to measure the largest fraction of the 5-CH3H4PteGlu coming from the tracer (mass 464; M + 6) and the largest fraction coming from the tracee (mass 458; M + 0). The response for either M + 0 or M + 6 will depend on the number of 5-CH3H2PteGlu molecules present in the sample that have come from the two sources. Examining each source separately, the number of 5-CH3H2PteGlu molecules in the sample, measured in the M + 6 channel, that have come from the tracer (defined as M + 6tracer) is proportional to the number of mol of the tracer present in the sample (defined as moltracer) and the fraction of the tracer that is actually present at mass 464 (defined as M + 6tracer). Therefore:

\[ M + 6_{\text{sample}} \propto M + 6_{\text{tracer}} \times \text{mol}_{\text{tracer}}. \]

and, similarly for M + 0sample,

\[ M + 0_{\text{sample}} \propto M + 0_{\text{tracer}} \times \text{mol}_{\text{tracer}} + M + 0_{\text{tracee}} \times \text{mol}_{\text{tracee}}. \]  

On dividing (2) by (1):

\[ \frac{M + 6_{\text{sample}}}{M + 0_{\text{sample}}} = \frac{M + 6_{\text{tracer}} \times \text{mol}_{\text{tracer}} + M + 6_{\text{tracee}} \times \text{mol}_{\text{tracee}}}{M + 0_{\text{tracer}} \times \text{mol}_{\text{tracer}} + M + 0_{\text{tracee}} \times \text{mol}_{\text{tracee}}}. \]  

The ratio M + 6sample/M + 0sample is defined as \( \frac{M+6}{M+0R} \). Therefore:

\[ \frac{M+6}{M+0R} = \frac{M + 6_{\text{tracer}} \times \text{mol}_{\text{tracer}} + M + 6_{\text{tracee}} \times \text{mol}_{\text{tracee}}}{M + 0_{\text{tracer}} \times \text{mol}_{\text{tracer}} + M + 0_{\text{tracee}} \times \text{mol}_{\text{tracee}}}. \]  

Similarly for the M + 0sample/M + 0sample ratio:

\[ \frac{M+0}{M+0R} = \frac{M + 0_{\text{tracer}} \times \text{mol}_{\text{tracer}} + M + 0_{\text{tracee}} \times \text{mol}_{\text{tracee}}}{M + 0_{\text{tracer}} \times \text{mol}_{\text{tracer}} + M + 0_{\text{tracee}} \times \text{mol}_{\text{tracee}}}. \]  

If the denominator in equations 4 and 5 is set to be a constant, k, then:

\[ k \times \frac{M+6}{M+0R} = 1/k = \frac{M + 0_{\text{tracer}} \times \text{mol}_{\text{tracer}} + M + 0_{\text{tracee}} \times \text{mol}_{\text{tracee}}}{M + 0_{\text{tracer}} \times \text{mol}_{\text{tracer}} + M + 0_{\text{tracee}} \times \text{mol}_{\text{tracee}}}. \]  

Equations 4 and 5 can now be rewritten:

\[ \frac{M+6}{M+0R} = \frac{M + 6_{\text{tracer}} \times k \times \text{mol}_{\text{tracer}} + M + 6_{\text{tracee}} \times \text{mol}_{\text{tracee}}}{M + 0_{\text{tracer}} \times \text{mol}_{\text{tracer}} + M + 0_{\text{tracee}} \times \text{mol}_{\text{tracee}}}; \]

\[ \frac{M+0}{M+0R} = \frac{M + 0_{\text{tracer}} \times k \times \text{mol}_{\text{tracer}} + M + 0_{\text{tracee}} \times \text{mol}_{\text{tracee}}}{M + 0_{\text{tracer}} \times \text{mol}_{\text{tracer}} + M + 0_{\text{tracee}} \times \text{mol}_{\text{tracee}}}. \]

Equations 7 and 8 can be represented in matrix notation:

\[ \begin{bmatrix} \frac{M+6}{M+0R} \\ \frac{M+0}{M+0R} \end{bmatrix} = \begin{bmatrix} M + 6_{\text{tracer}} & M + 6_{\text{tracee}} \\ M + 0_{\text{tracer}} & M + 0_{\text{tracee}} \end{bmatrix} \times \begin{bmatrix} k \times \text{mol}_{\text{tracer}} \\ k \times \text{mol}_{\text{tracee}} \end{bmatrix}, \]  

or,

\[ R = A \times x. \]  

Solving for x:

\[ x = A^{-1}R, \]  

where

\[ x = \begin{bmatrix} k \times \text{mol}_{\text{tracer}} \\ k \times \text{mol}_{\text{tracee}} \end{bmatrix}. \]
In terms of mol fractions:

mole fraction of tracer (i.e. \(5\text{MTHF}_{\text{fraction tracer}}\))

\[
\frac{k \times \text{mol}_{\text{tracer}}}{k \times \text{mol}_{\text{tracer}} + k \times \text{mol}_{\text{tracee}}},
\]

(12)

mole fraction of tracee (i.e. \(5\text{MTHF}_{\text{fraction tracee}}\))

\[
\frac{k \times \text{mol}_{\text{tracee}}}{k \times \text{mol}_{\text{tracer}} + k \times \text{mol}_{\text{tracee}}},
\]

(13)

It is now a simple task to calculate the quantity of the 5-\(\text{CH}_3\text{H}_4\text{PteGlu}\) that has come from the tracer or tracee in any plasma sample because the total 5-\(\text{CH}_3\text{H}_4\text{PteGlu}\) (defined as 5\text{MTHF}_{\text{total}}) in the sample is known from an HPLC measurement.

Quantity of tracer = \[
\frac{5\text{MTHF}_{\text{fraction tracer}} \times 5\text{MTHF}_{\text{total}}}{5\text{MTHF}_{\text{fraction tracer}} + 5\text{MTHF}_{\text{fraction tracee}}};
\]

(14)

Quantity of tracee = \[
\frac{5\text{MTHF}_{\text{fraction tracee}} \times 5\text{MTHF}_{\text{total}}}{5\text{MTHF}_{\text{fraction tracer}} + 5\text{MTHF}_{\text{fraction tracee}}};
\]

(15)