Tissue folates in fruit bats (*Rousettus aegyptiacus*) with nitrous oxide-induced vitamin $B_{12}$ deficiency and neurological impairment

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1. Long-term exposure of the fruit bat *Rousettus aegyptiacus* to nitrous oxide, which inactivates methylcobalamin, leads to neurological impairment and ataxia.

2. In N$_2$O-exposed animals, liver concentrations of total folates and methyl folates decreased to less than one-fifth that of control animals. *Pediococcus cerevisiae*-active folates were also reduced.

3. In brain, there were no changes in total or methyl folates, but *P. cerevisiae*-active folates were lower in N$_2$O-exposed animals.

4. Supplementation with methionine retarded the development of neurological impairment and the fall in liver total and methyl folates, but not that in *P. cerevisiae*-active folates.

5. Supplementation with serine failed to retard the development of neurological impairment or fall in hepatic folates.

6. The present results suggest that the N$_2$O-induced neurological impairment in the bat is not related to depletion of cerebral folates, but do not exclude changes in the subcellular distribution of folates.

Study of the mechanism of the neurological impairment associated with vitamin $B_{12}$ deficiency has been difficult owing to the lack of a suitable small-animal model in which vitamin $B_{12}$ deficiency with neurological changes can be induced rapidly. This has been overcome by the observation that exposure of the fruit bat (*Rousettus aegyptiacus*) to the anaesthetic gas nitrous oxide leads to severe neurological impairment progressing to paralysis and death after 8–12 weeks' exposure (van der Westhuyzen et al. 1982a). N$_2$O inactivates methylcobalamin by oxidizing cob(I)alamin to cob(III)alamin (Banks et al. 1968), thereby inactivating the enzyme methionine synthetase (5-methyltetrahydrofolate homocysteine methyltransferase; EC 2.1.1.13; MS) which requires cob(I)alamin as a cofactor (Deacon et al. 1980a; Chanarin et al. 1985). Depletion of tissue vitamin $B_{12}$ stores follows long-term exposure to N$_2$O (van der Westhuyzen et al. 1982a).

The basic lesion whereby vitamin $B_{12}$ deficiency or inactivation leads to neurological impairment is uncertain. Ever since the clinical observation that folic acid apparently aggravated the neurological changes in humans suffering from vitamin $B_{12}$ deficiency (in the form of pernicious anaemia), these changes have been thought to be related somehow to folic acid metabolism.

Inactivation of cobalamin by N$_2$O has profound effects on folic acid metabolism in the rat, including changes in plasma levels (Lumb et al. 1981a), loss of tissue folates (Lumb et al. 1981b), impairment of folate polyglutamate synthesis from unsubstituted folates (Perry et al. 1979a) and impaired uptake of folate analogues by the liver (McGing et al. 1978; Chanarin et al. 1985). However, the rat does not develop neurological lesions on exposure to N$_2$O and is thus not a suitable animal model. Furthermore, in the reported studies in the rat, exposure to N$_2$O has been acute (up to 10 d), and thus not entirely relevant to the development of vitamin $B_{12}$-related neurological changes, which require longer periods of N$_2$O exposure.
The neurological complications of vitamin B₁₂ deficiency may be related to changes in folates in the brain. In the present report, cerebral and hepatic folates in control and neurologically-impaired fruit bats following long-term exposure to N₂O have been examined. As methionine has been shown to protect partially against the neurological changes in the N₂O-exposed bat (van der Westhuyzen et al. 1982a; van der Westhuyzen & Metz, 1983), a group of animals who received dietary supplementation with methionine was included. In a further group, serine was given as a dietary supplement instead of methionine to detect a possible effect of an augmented supply of methylene groups on tissue folates.

MATERIALS AND METHODS

The study was approved by the Animal Ethics Committee of the University of the Witwatersrand Medical School.

Experimental animals

Fruit bats caught in the wild were kept in vivaria partially exposed to the natural day–night cycle. All animals were fed on a pest-free, all-fruit diet supplemented with 0·2 ml of a vitamin B₁₂-free oral vitamin preparation (Abidec; Parke-Davis, New York) fortnightly. The folic acid content of the diet was approximately 0·22 mg/kg edible portion (largely sliced banana). Since the bats consume food equivalent to three-quarters of their body-weight/d, the daily intake of folic acid was similar to that of rats consuming a diet mixture containing 1 mg folic acid/kg. Control animals received 5 μg cyanocobalamin/kg body-weight fortnightly, and maintained normal vitamin B₁₂ nutrition (van der Westhuyzen et al. 1982a). Test animals which were exposed to N₂O were randomly allocated to the following dietary groups: (1) N₂O group, standard all-fruit diet; (2) N₂O + meth group, fruit supplemented with l-methionine (99%; Riedel-de Haën, Hanover, West Germany) at the rate of 600 mg/kg fruit. This supplement provided approximately 60 mg methionine/animal per d (0·3 g/kg body-weight), sufficient to delay significantly the onset of neurological impairment but low enough not to lead to sudden death (van der Westhuyzen & Metz, 1984). (3) N₂O + ser group, fruit supplemented with l-serine (Sigma, St Louis, Mo., USA) at the rate of 700 mg/kg fruit, which provided 70 mg serine/animal per d (0·53 g/kg body-weight).

Exposure to N₂O

Experimental bats were exposed to an atmosphere of oxygen–N₂O (50:50, v/v) daily for 90 min in a specially constructed cabinet in which water vapour and carbon dioxide were controlled. Exposure was continued until the animals showed unequivocal neurological impairment in the form of ataxia, at which stage they were killed (7·5–9·5 weeks) by exsanguination.

Extraction of tissue

Within 90 s of death, the brain and liver were removed, weighed, mashed and placed in 10 vol. ascorbate (10 g/l solution, pH 6·0) in a 95° water-bath. After boiling for 7 min to destroy endogenous folate conjugase activity, the tissue was cooled on ice, homogenized with a Potter–Elvehjem homogenizer and centrifuged at 15000 g for 20 min at 4°. The supernatant fractions were stored in the dark at −20° until assayed.

Folate assays

Folates were measured by microbiological assay after papain treatment. This method of folate release yields results comparable to those obtained with conjugase prepared from
Table 1. Physical changes in fruit bats (Rousettus aegyptiacus) exposed to nitrous oxide and the effect of dietary supplements

(Mean values with their standard errors)

<table>
<thead>
<tr>
<th>Group</th>
<th>n</th>
<th>Initial</th>
<th>Final</th>
<th>Duration of exposure (d)</th>
<th>Condition of group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Body-wt (g)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>SE</td>
<td>Mean</td>
<td>SE</td>
</tr>
<tr>
<td>N2O</td>
<td>13</td>
<td>124</td>
<td>4</td>
<td>107**</td>
<td>3</td>
</tr>
<tr>
<td>N2O+serine</td>
<td>7</td>
<td>132</td>
<td>4</td>
<td>111***</td>
<td>3</td>
</tr>
<tr>
<td>N2O+methionine</td>
<td>6</td>
<td>119</td>
<td>3</td>
<td>138**</td>
<td>3</td>
</tr>
</tbody>
</table>

Mean values were significantly different, indicating a change in weight: ** P < 0.01, *** P < 0.001.

RESULTS

Clinical findings

The findings are summarized in Table 1. The effect of N2O exposure on the bats followed the pattern observed in previous studies (van der Westhuysen et al. 1982a; van der Westhuysen & Metz, 1983). Exposed animals lost weight and developed neurological changes manifest by impairment in climbing and flying, and in ataxia. Supplementation of the diet with methionine prevented the weight loss and retarded the development of neurological impairment, and none of these animals was ataxic after 9 weeks of exposure. Supplementation with serine did not prevent or retard the effects of exposure to N2O.

Liver folates

The results are shown in Table 2. The mean concentration of total (L. casei) folates in the livers of control animals was 537 mg/g, of which 90% were methyl folates. In the N2O-exposed animals, total folates had fallen severely to a mean value of 87 ng/g with 94% as
Table 2. The effect of nitrous oxide exposure on folates in the liver of the fruit bat (Rousettus aegyptiacus) (Mean values with their standard errors)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>SE</th>
<th>Mean</th>
<th>SE</th>
<th>%†</th>
<th>Mean</th>
<th>SE</th>
<th>%†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated controls</td>
<td>537</td>
<td>111</td>
<td>485</td>
<td>113</td>
<td>90.3</td>
<td>158</td>
<td>17</td>
<td>29.4</td>
</tr>
<tr>
<td>N₂O</td>
<td>87***</td>
<td>15</td>
<td>82**</td>
<td>14</td>
<td>94.3</td>
<td>24***</td>
<td>2</td>
<td>19.7</td>
</tr>
<tr>
<td>N₂O + serine</td>
<td>70**</td>
<td>10</td>
<td>65**</td>
<td>10</td>
<td>92.9</td>
<td>24**</td>
<td>2</td>
<td>34.6</td>
</tr>
<tr>
<td>N₂O + methionine</td>
<td>323</td>
<td>105</td>
<td>312</td>
<td>105</td>
<td>96.6</td>
<td>36**</td>
<td>5</td>
<td>11.0</td>
</tr>
</tbody>
</table>

Mean values were significantly different from those of the control group: ** P < 0.01, *** P < 0.001.
† Percentage of total folates.

Table 3. The effect of nitrous oxide exposure on folates in the brain of the fruit bat (Rousettus aegyptiacus) (Mean values with their standard errors)

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean</th>
<th>SE</th>
<th>Mean</th>
<th>SE</th>
<th>%†</th>
<th>Mean</th>
<th>SE</th>
<th>%†</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated controls</td>
<td>44.8</td>
<td>2.1</td>
<td>41.5</td>
<td>1.9</td>
<td>92.6</td>
<td>16.0</td>
<td>0.9</td>
<td>35.7</td>
</tr>
<tr>
<td>N₂O</td>
<td>41.8</td>
<td>2.9</td>
<td>38.0</td>
<td>2.7</td>
<td>90.9</td>
<td>9.8*</td>
<td>0.9</td>
<td>23.9</td>
</tr>
<tr>
<td>N₂O + serine</td>
<td>46.1</td>
<td>6.9</td>
<td>40.3</td>
<td>6.2</td>
<td>87.4</td>
<td>13.2*</td>
<td>3.1</td>
<td>28.6</td>
</tr>
<tr>
<td>N₂O + methionine</td>
<td>44.3</td>
<td>7.6</td>
<td>40.2</td>
<td>7.0</td>
<td>90.7</td>
<td>8.4*</td>
<td>2.1</td>
<td>19.0</td>
</tr>
</tbody>
</table>

Mean values were significantly different from those of the control group: * P < 0.05, ** P < 0.01.
† Percentage of total folates.

methyl folates. The ratio, methyl-THF: non-methylated THF therefore increased in the N₂O-exposed livers, but the increase was modest.

The fall in *P. cerevisiae*-active folates was even greater, from a mean concentration of 158 ng/g in control animals to one of 24 ng/g in the N₂O-exposed group.

In the N₂O-treated animals supplemented with methionine, the degree of fall in total folates was less and the mean was not significantly lower than the mean of the control animals. The percentage of methyl forms (96.6) was similar to that of animals treated with N₂O only. In contrast to its effect on total folates, methionine had no significant effect on the fall in *P. cerevisiae* activity following N₂O exposure.

Supplementation with serine had no significant effect on the fall in total folates, methyl forms or the *P. cerevisiae* values, compared with N₂O exposure without serine.

**Brain folates**

The results are shown in Table 3. In contrast to the fall in liver folates, exposure to N₂O failed to produce any significant change in the concentrations of methyl or total folates in
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discussion

The neurological impairment induced by N\textsubscript{2}O in the fruit bat bears both resemblances and differences to that of man and non-human primates. The development of ataxia in the N\textsubscript{2}O-exposed monkey (Scott et al. 1981) is similar (as far as comparisons allow) to that of the bat. Both exhibit shaking of the limbs at an early stage, followed later by difficulties with climbing leading to ataxia. In both species, the development of the neuropathy is considerably ameliorated by methionine supplementation. Pronounced histological changes resembling those of classical subacute combined degeneration in man, have been described in ataxic monkeys (Scott et al. 1981). However, although patchy spongiose change suggestive of early demyelination has been observed in the spinal cord of fruit bats maintained on a vitamin B\textsubscript{12}-deficient diet for several years (Green et al. 1975), clear histological changes have not been observed in bats with neurological impairment induced by N\textsubscript{2}O (van der Westhuyzen et al. 1982a). Time may be a factor here, as the monkey survives in the moribund state for 2 to 3 weeks, while the fruit bat dies within 1 to 2 d of becoming moribund. In contrast to the bat and monkey, mice and rats remain healthy when exposed to N\textsubscript{2}O for protracted periods (Chanarin et al. 1985).

Changes in liver and brain folates have been reported in rats exposed for 5 or 10 d to N\textsubscript{2}O (McGing et al. 1978; Lumb et al. 1980, 1981b). In rats there is a marked fall in L. casei folate activity in the liver to about 16\% of that of control animals. P. cerevisiae activity shows a similar fall, of a somewhat lesser degree. There is little or no fall in L. casei folate activity in the brain but some fall in P. cerevisiae activity. The results of the present study of bats exposed long-term to N\textsubscript{2}O are essentially similar.

The fall in total and methyl folates in the liver is related to the inhibition of the enzyme MS by N\textsubscript{2}O. In the rat, MS activity in the liver after long-term N\textsubscript{2}O exposure is only 5\% that of control animals (van Tonder et al. 1986). Following inhibition of this enzyme, the methylation of homocysteine to methionine via donation of the methyl group of methyl-THF is impaired. Hepatic uptake of folate analogues is impaired in the N\textsubscript{2}O-exposed rat (McGing et al. 1978; Lumb et al. 1982). The non-methylated methyl-THF is then excreted in the urine (Lumb et al. 1982) and the liver stores are depleted (Lumb et al. 1980).

The response of brain folates to N\textsubscript{2}O is different to that of the liver in that there is no fall in total or methyl folates. Similar observations were made in the rat exposed to N\textsubscript{2}O for 5 d (Lumb et al. 1981b) and in the vitamin B\textsubscript{12}-deficient fruit bat (Perry et al. 1979b). The enzyme MS occurs in the brain of both the rat and the fruit bat, and is inhibited by N\textsubscript{2}O in both animals (Deacon et al. 1980a; Lumb et al. 1983; van der Westhuyzen & Metz, 1983). This inactivation is comprehensive. Therefore, there must be some mechanism which protects brain folates following inhibition of MS. There is possibly some redistribution of folates from liver to other tissues, as in the N\textsubscript{2}O-exposed rat (Lumb et al. 1981b). The extremely slow turnover of total folates in brain (Carl et al. 1980) is also important, since this leads to a limited demand for folates from the blood. Moreover, selective concentration of folates occurs in the cerebrospinal fluid (CSF) (Herbert & Zalusky, 1961) with rapid transport of 5-methyl-THF into CSF from serum (Spector & Lorenzo, 1975). In the fruit bat, only 5-methyl-THF is taken up by brain tissue, and uptake is similar in control and
vitamin B₁₂-deficient animals (Perry et al. 1979b). It is possible then that the uptake of circulating folates by brain tissue leads to preservation of total and methyl folates in the brain despite inhibition of MS.

The action of methionine in partially protecting the N₂O-exposed bat against the development of neurological impairment was confirmed in the present study. Methionine prevented, but not completely, the fall in liver folates, a finding compatible with the report by Eells et al. (1982) that methionine prevents the decrease in liver THF in rats exposed for 4 h to N₂O, and by Perry et al. (1983) who has demonstrated that methionine restores the capacity of the N₂O-treated rat to utilize THF.

The mechanism whereby methionine retards the depletion of total and methyl folates in the liver of the N₂O-exposed animal is uncertain. It has been suggested that methionine impairs the recycling of THF into 5-methyl-THF through its conversion to S-adenosylmethionine which inhibits the enzyme 5,10-methylene-THF reductase (FADH₉) (EC 1.7.99.5), responsible for the production of 5-methyl-THF (Kutzbach & Stokstad, 1967). THF is thus released for other metabolic functions. Perry et al. (1983) have suggested that the corrective effect of methionine is by supply of formate for the formylation of THF. In the present study, methionine failed to preserve the concentration of P. cerevisiae-active folates in both liver and brain, and the lowest levels of unsubstituted reduced or formyl-substituted folates occurred in the brain of animals supplemented with methionine. The fall in these folates in the brain of N₂O-exposed bats is thus unlikely to be causally related to the neuropathy, for the effect of methionine in protecting against neurological impairment was not accompanied by preservation of the concentration of these folates (which include 5- and 10-formyl-THF). Furthermore, supplementation with serine retarded the fall of P. cerevisiae-active folates in the brain of half the animals but failed to protect against the neurological impairment.

The catabolism of serine in rat liver proceeds mainly by way of the serine hydroxymethyltransferase reaction in which THF is converted to methylene-THF (Yoshida & Kikuchi, 1970). This enzyme is not inhibited by N₂O (Deacon et al. 1980b) and supplementation of the N₂O-exposed animal with serine would be expected to supply additional methylene-THF and 5-methyl-THF, the latter via the enzyme 5,10-methylene-THF reductase (FADH₉). The failure of serine to prevent the fall in liver methyl-THF suggests inability by the N₂O-exposed animal to use additional amounts of methylene generated owing to lack of THF. THF deficiency may arise as a result of the inability to transfer the methyl group from 5-methyl-THF, or from a decrease in the size or availability of the postulated non-methylated pool of circulating folates in this species (Perry et al. 1979c; van Tonder et al. 1986).

The preservation of the concentration of total and methyl folates in the brain of bats with neurological impairment following vitamin B₁₂ inactivation, does not lend support to the theory that the neuropathy of vitamin B₁₂ deficiency is related to depletion of cerebral folates, mediated by inactivation of MS with its methylcobalamin cofactor. It has been suggested rather that the neurological changes may result from other vitamin B₁₂-dependent functions, such as impairment of the adenosylcobalamin-dependent methylmalonyl-CoA mutase (EC 5.4.99.2) reaction, which leads to limited changes in odd-chain fatty acid metabolism (Frenkel, 1973; Fehling et al. 1978; Peifer & Lewis, 1979; van der Westhuyzen et al. 1983), or some other undescribed metabolic functions of vitamin B₁₂. In the fruit bat, neurological changes associated with vitamin B₁₂ deficiency appear not to be related to the accumulation of cobalamin analogues (van der Westhuyzen et al. 1982b).

In conclusion, it is possible that the overall level of folates in the brain is less important than the regional and subcellular distribution of these compounds. For example, the
activity of MS in the normal mouse is high in synaptosomes, suggesting that MS may have some synaptosomal-specific function (Carl et al. 1980). The results of the present study do not rule out the possibility of changes in the subcellular or regional distribution of folates.

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