Megaloblastic anaemia, cobalamin, and folate

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SUMMARY Developments relating to cobalamin and folate are reviewed. Current work on the relations between these two coenzymes are discussed, particularly those that have emerged in studies using nitrous oxide, which inactivates cobalamin.

During the 1960s many ideas were developed about the megaloblastic anaemias. Cobalamin assays on human sera, initially at the Royal Postgraduate Medical School, had been consolidated, and patients with megaloblastic anaemia could be grouped into those with low B₁₂ concentrations and those with normal concentrations. Isotopically labelled B₁₂ became available and B₁₂ absorption tests became part of clinical practice. A method for the assay of serum folate was described and was quickly extended to the more useful red cell folate assay. By the end of 1963 an assay for the intrinsic factor content of gastric juice and for the detection of antibodies in serum to intrinsic factor had been introduced as well as methods for detecting gastric parietal cell antibodies.

The use of urinary formiminoglutamic acid (Figlu) as a test for folate deficiency reared its ugly head. And, finally, two groups put forward a hypothesis to account for the strange interrelation between B₁₂ and folate that came to be known as the methylfolate trap hypothesis.

This review covers the developments of the past quarter century and how the ideas of 25 years ago have stood the test of time.

Automated cell counters and mean corpuscular volume

The introduction into haematology laboratories of accurate and sophisticated blood counting machines is the major technical development of the past 25 years. It has highlighted the value of red cell size (mean corpuscular volume, MCV) in diagnosis and emphasised the raised MCV in many disorders that are unrelated to impairment of B₁₂ and folate metabolism. Normoblastic macrocytosis occurs in chronic alcoholism, hypothyroidism, normal pregnancy, healthy neonates, marrow failure, chronic haemolytic states with raised reticulocyte values, many preleukaemic (myelodysplastic) disorders, and treatment with many cytotoxic drugs including, chlorambucil, mephalan, methotrexate, azathioprine etc. Finally, there is a common macrocytosis occurring in premenopausal women whose only complaint is lassitude, which remains unexplained.

Not all patients with megaloblastic anaemia will have an increased MCV. Some who have thalassaemia trait, anaemia of chronic disorders, or concurrent iron deficiency may have a frankly megaloblastic marrow with a normal MCV. When treated with B₁₂ or folate, or both, the MCV falls to that associated with the underlying disorder below the normal range of 80 to about 94 fl.

Finally, there is no agreement as to what constitutes the normal MCV: quoted ranges vary from 76 at the lower end to 108 fl at the upper end. This is because there is no absolute way to obtain this value and the machine methods relate to the manner in which the settings are manipulated.

The serum cobalamin (B₁₂) concentration

The early assays for B₁₂ were all microbiological assay procedures, and in essence these gave similar results. The assays were tedious to perform and often assays were rejected because of loss of purity of the organism, introduction of extraneous B₁₂ in the assay system, and poor growth of the assay organism. For these reasons the development of an alternative method based on dilution of isotopically labelled B₁₂ by the native B₁₂ in a serum sample (saturation analysis) was widely welcomed. These assays lent themselves to the preparation of commercial kits that have become the mainstay of laboratory assays.

It soon became apparent that often a lot more B₁₂ was being measured by the isotope methods than microbiological methods. Thus the lower limit of the normal range could be 300 pg/ml with an isotope assay but was about 170 pg/ml by microbiological assay. A value of 250 pg/ml was low by isotope assay but plumb normal when assayed microbiologically.

When performing the isotope assay, a standard amount of [³⁵Co]B₁₂ is added to an extract of serum...
containing a varying amount of native B₁₂. The next step is to take out an aliquot of the B₁₂ in the mixture: this is done by adding a B₁₂ binding protein. The greater the amount of native B₁₂ the greater the dilution of \(^{57}\text{Co}\)B₁₂, and hence less \(^{57}\text{Co}\)B₁₂ will attach to the binder (fig 1). The explanation of the discrepancy between isotope and microbiological assay lay in the nature of the B₁₂ binding protein used in the assay. When purified gastric intrinsic factor was used as the B₁₂ binding protein the results were similar to those obtained by microbiological assay. When other B₁₂ binders, such as those present in serum or in saliva—collectively termed R-binders—were used the result was always higher than that obtained with microbiological assay. Kolhouse et al\(^{14}\) suggested that the R-binders were picking up forms of B₁₂ in serum not picked up by intrinsic factor. This suggestion was shown to be correct by cross absorption studies.\(^{15}\) By attaching intrinsic factor to polyacrylamide beads and adding these to serum extracts, all B₁₂ analogues detectable both by microbiological assay and an isotope method with intrinsic factor were removed. The serum extract, however, still had B₁₂ activity detected by an isotope assay with an R-binder. It now seems that microbiological assays measure about half the B₁₂ present in serum. The same analogues are measured by microbiological assay and an intrinsic factor isotope assay.\(^{16}\)

The identity of the B₁₂ analogues undetected by microbiological assay remains unknown and its origin is equally conjectural. In practice, an isotope assay for B₁₂ using purified intrinsic factor is preferred because it gives a marginally better distinction between normal and B₁₂ deficient sera,\(^{17}\) but claims that large numbers of patients deficient in B₁₂ were missed because R-binder assays were used, are exaggerated. Failure to detect low B₁₂ concentrations is more likely to be due to a badly designed and badly performed assay than to the nature of the binder.

Finally, it is widely believed that a low serum B₁₂ concentration is synonymous with B₁₂ deficiency. This is not the case.\(^{10}\) B₁₂ deficiency is the commonest cause of low B₁₂ concentration, but there are other causes. One third of patients with megaloblastic anaemia due to folate deficiency have low B₁₂ concentrations, which return to normal within days of treatment with folic acid.\(^{18}\) Low B₁₂ concentrations are common near term in normal pregnancy, in patients with iron deficiency, after partial gastrectomy as well as in treated epileptics. Low B₁₂ concentrations are often found in otherwise perfectly healthy people. Except in vegetarians with nutritional B₁₂ deficiency, all patients with clinically important low B₁₂ concentrations also have impaired B₁₂ absorption. Where B₁₂ absorption is normal and the patient is taking a mixed diet, a low B₁₂ concentration is of no clinical importance.

**B₁₂ Absorption**

Tests for B₁₂ absorption have become important and

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**Fig 1** When \[^{57}\text{Co}\]B₁₂ is mixed with intrinsic factor (in this example intrinsic factor is attached to a solid matrix), some B₁₂ attaches to intrinsic factor and, when B₁₂ is present in excess, some remains free. When, in addition to \[^{57}\text{Co}\]B₁₂, B₁₂ is also present from the serum sample under test, the \[^{57}\text{Co}\]B₁₂ is diluted and hence the B₁₂ binding to intrinsic factor is a mixture of \[^{57}\text{Co}\]B₁₂ and native B₁₂ from serum. Thus the more native B₁₂ present the greater the dilution of the \[^{57}\text{Co}\]B₁₂, and this is the basis on which the assay is performed.
reliable indicators of ileal function and of availability of gastric intrinsic factor. It is less widely appreciated how often misleading results are recorded because of incomplete urine collection.\(^9\) Assessment of the result by measuring the radioactivity of the labelled B\(_{12}\) in plasma collected after eight to 12 hours is as reliable an indicator of the result as a complete urine collection; it should be mandatory to insure against loss of urine, which occurs in between 25 to 50% of all tests, and in most tests carried out in the elderly, by combining the standard Schilling test with measurement of plasma radioactivity.

In addition to the known permutations of the B\(_{12}\) absorption test by giving B\(_{12}\) with intrinsic factor, performing the test after antibiotics etc, it has been suggested that additional information can be obtained by “binding” the labelled B\(_{12}\) to protein. Some have bound the labelled B\(_{12}\) to chick serum,\(^20\) others have cooked the B\(_{12}\) with egg and served up an aliquot of this material.\(^{21}\) The test thus requires digestive processes to release B\(_{12}\) from this unpromising material so that it can bind to intrinsic factor, which in turn will enable B\(_{12}\) to be absorbed. Even normal subjects are unable to achieve normal B\(_{12}\) absorption with this method, the mean urinary excretion with egg white being between 2.7 to 4.0% of a 1-68 \(\mu\)g oral dose and 5-1 to 6-0 with egg yolk. By contrast, the mean result in the standard Schilling test was 23.6%. Normal has been defined as the B\(_{12}\) absorption of aqueous B\(_{12}\) or absorption of food B\(_{12}\) as natural B\(_{12}\) in lamb.\(^22\) Not surprisingly, achlorhydric patients and patients after gastric surgery fare even worse than controls with protein bound B\(_{12}\). This is presumably because they cannot activate pepsinogen to aid proteolytic digestion of the binding proteins. The test has been interpreted, however, as detecting a lack of intrinsic factor at a stage when the standard B\(_{12}\) absorption test is still normal. There are no available data to suggest that this is likely; nor is there any evidence that the test is of any clinical value.

Dietary B\(_{12}\) is present either as part of methionine synthetase or as part of methylmalonyl CoA-mutase. Small amounts are linked to R-binders. Once B\(_{12}\) is released from the holoenzyme, much of it links to R-binder mainly from saliva, although R-binder is also present in gastric and intestinal juice. Pancreatic enzymes serve to release B\(_{12}\) from its R-binder link and permit its uptake by intrinsic factor. In pancreatitis B\(_{12}\) absorption is impaired because of failure to degrade the R-binder. Brugge\(\text{et al}\)\(^{23}\) devised a suitable B\(_{12}\) absorption test in which the absorption of B\(_{12}\) bound to R-binder is compared with absorption of B\(_{12}\) bound to intrinsic factor. With controls, the Schilling test result with B\(_{12}\) and intrinsic factor was 21-2%, and with R-binder, 16-2%. With pancreatic disease the absorption of B\(_{12}\) with intrinsic factor was 16-3% and with R-binder only 1-0%. The combination is clearly of value in the diagnosis of chronic pancreatic disease.

There remain unresolved problems in relation to B\(_{12}\) absorption in patients with atrophic gastritis and after partial gastrectomy, where there is no clear correlation between the serum B\(_{12}\) concentration and the results of standard B\(_{12}\) absorption tests.

**Intrinsic factor, its assay, and its antibody**

Intrinsic factor, necessary for the intestinal absorption of B\(_{12}\), is secreted by the gastric parietal cell. An assay of intrinsic factor was introduced simultaneously by Ardeman \(\text{et al}\)\(^4\) and Abels \(\text{et al}\) in 1963.\(^5\) The problem in developing such an assay is that gastric juice has at least three B\(_{12}\) binding proteins: intrinsic factor, partially digested intrinsic factor, and R-binder. When labelled B\(_{12}\) is added to gastric juice some binds to all three components, hence the binding of B\(_{12}\) alone cannot be used as a measure of intrinsic factor. Each of these binding proteins, however, can be prevented from taking up B\(_{12}\). An intrinsic factor antibody present in serum in more than half the patients with pernicious anaemia, and when added to gastric juice, will react with intrinsic factor and prevent B\(_{12}\) uptake by intrinsic factor. Thus B\(_{12}\) binding is now due only to R-binder, and when this value is subtracted from the total B\(_{12}\) binding of gastric juice, it is a measure of intrinsic factor content. One unit of intrinsic factor is the amount binding 1 ng of B\(_{12}\).

Cobinamide is a B\(_{12}\) analogue that lacks the benzimidazole moiety. It binds firmly to R-binder but not at all to intrinsic factor. Addition of cobinamide to gastric juice will block the R-binder, so that subsequent addition of labelled B\(_{12}\) will bind only to intrinsic factor.\(^{24}\)

Assay of intrinsic factor has confirmed its virtual disappearance in pernicious anaemia; there is a vast excess present in healthy subjects. Only 1% of the normal daily output is required for normal B\(_{12}\) absorption.\(^{10}\) Finally, abnormal forms of intrinsic factor have been shown in megaloblastic anaemia in infancy—that is, these have bound labelled B\(_{12}\) but have failed to potentiate its intestinal absorption.\(^{25}\)

Detection of antibody to intrinsic factor is a useful aid in diagnosis of pernicious anaemia but, rarely, this antibody can be present in patients with Graves’ disease, atrophic gastritis etc in the absence of pernicious anaemia.\(^{26}\) More than 40% of patients with pernicious anaemia, however, do not have such an antibody in serum but may have it in the gastric secretion, when it is likely to be an IgA immunoglobulin rather than an IgG as in serum. Even those who lack humoral antibody against intrinsic factor generally show evidence of cell mediated immunity against intrinsic fac-
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The importance of cell mediated immunity is shown by the high incidence of pernicious anaemia in patients with acquired hypogammaglobulinemia, 30% of whom develop the disease. These patients are unable to form humoral antibodies. These intrinsic factor antibodies are able to neutralise residual intrinsic factor secretion, or damage intrinsic factor secreting cells and convert to a just adequate B₁₂ absorption (present in simple atrophic gastritis) to an inadequate one so that a strong negative B₁₂ balance develops. This is soon followed by clinically overt pernicious anaemia.

B₁₂ transport proteins

R-protein (transcobalamins I and III) is present in all body fluids and most cells. A physiological role for these glycoproteins has not been identified. TC III in plasma is largely shed from leucocytes.

Transcobalamin II is the prime transport protein for B₁₂. It has a molecular weight of 35 000 daltons and is produced by the liver, macrophages, and ileal enterocytes. It is essential for moving B₁₂ out of the ileal enterocyte to plasma during B₁₂ absorption and for uptake of B₁₂ by cells. There are specific receptors for TC II, and TC II is internalised into cells by endocytosis. In the absence of TC II a severe B₁₂ deficient megaloblastic anaemia develops, usually within six weeks of birth, which has to be treated with very large doses of B₁₂ (1000 μg two to three times a week) so that some enters cells by passive diffusion. Even B₁₂ present in serum on R-binder in TC II deficiency cannot be used because of lack of the transport protein, so that paradoxically normal serum B₁₂ concentration occurs concomitantly with severe tissue depletion of B₁₂.

Folates

Assay of folate concentration with Lactobacillus casei in serum and whole blood has provided data that are similar to those resulting from B₁₂ assay. A low serum folate concentration probably represents a state of negative folate balance and may be found in one third of all hospital patients. Red cells, on the other hand, contain some 30 times more folate than serum. Folate is incorporated into the red cell in the marrow by the developing erythroblast, and there is no folate turnover by mature red cells. Thus folate is locked in the red cell for the duration of its life span. Change in red cell folate comes from release of red cells from the marrow of different folate content. A low red cell folate represents established folate deficiency, irrespective of whether the subject is normoblastic or megaloblastic. Unfortunately, isotope methods used to assay folate have concentrated on the trivial serum folate assay and not on the clinically important red cell assay.

Urinary Figlu excretion is too sensitive for diagnosing folate deficiency for routine clinical practice. Like the serum folate concentration, abnormal results are found in one third of hospital patients, and it is no longer used.

The nature and function of intracellular folates have been clarified to a large extent. The folate analogue that is absorbed from food and which circulates in body fluids is 5-methyltetrahydrofolate. There is some suggestive evidence for a membrane associated transport protein that facilitates its entry into cells. Once in the cell, additional glutamic acid residues are added to give a form with 5-glutamic acid residues, although analogues with 4, 6, and 7 residues are present. In this form the folate (now termed folate polyglutamate) is retained in the cell and serves as the active coenzyme in transfer of single carbon units for purine, pyrimidine, and methionine synthesis. Cells that have lost the ability to make polyglutamates cannot grow unless the end products of folate metabolism such as purines are supplied.

The folate antagonist methotrexate is also taken into the cell and is converted into a polyglutamate in which form it persists in the cell over a long period. Not all intracellular folate is polyglutamate and about one third has one glutamic acid residue.

The deoxurydine (dU) suppression test

This test, which was modified by Metz et al from the original account by Killman, assesses the manner in which marrow cells convert deoxurydine into deoxythymidine. The single carbon unit required in this step (methylene or -CH₂-) is supplied by 5, 10-methylene tetrahydrofolate. An aliquot of marrow cells is incubated with deoxurydine. Normal cells will meet about 95% of their thymidine requirements by synthesis from deoxurydine. The results of the test are assessed by adding preformed [³H]thymidine. The remaining 5% requirement for thymidine is met by using this labelled compound.

Marrow cells from megaloblastic patients are unable to methylate deoxurydine as well as normal cells, and less than 90% is used and more than 10% [³H]thymidine is taken up into DNA. If B₁₂ is added to a further aliquot of marrow cells there is some correction of the impairment in B₁₂ deficient marrows but no correction with those deficient in folate. Formyltetrahydrofolate (such as folic acid) will correct the impairment in both B₁₂ and folate deficiency.

The dU suppression test is a test for "megaloblastosis" and provides an indication of the nature of the deficiency when it is combined with addition of B₁₂ or folate to the incubation mixtures. It is, how-
ever, time consuming, the manipulations taking the better part of a day.

Cobalamin-folate interrelations

The methylfolate trap hypothesis to explain B₁₂ folate interrelations was proposed just over 25 years ago.⁸⁻⁹ Both B₁₂ and folate are required for the synthesis of methionine (fig 2). The methyl group from methylfolate is passed on to homocysteine to form methionine, and B₁₂ is an intermediary in this transfer. In the absence of B₁₂ this pathway is interrupted. Two further observations led to the formulation of the methylfolate trap hypothesis.

1. The thermodynamics of the reaction by which methylfolate is formed from methylenetetrahydrofolate (5, 10, CH₂ folate—→5-CH₃ folate) is strongly shifted to the right—that is, on the basis of in vitro studies it was concluded that once methylfolate was formed it was improbable that it could be oxidised back to methylenetetrahydrofolate.

2. In untreated pernicious anaemia the serum folate (largely methylfolate) is increased. It was therefore deduced that in B₁₂ deficiency methylfolate could not be used, it could not be oxidised back to methylenetetrahydrofolate, and as more folate accumulated in the methyl form a shortage of other folate analogues emerged. It was consequently supposed that there was impaired transfer of formyl for purine synthesis and methylene transfer for thymidine synthesis and that this led to interference with DNA synthesis and megaloblastosis. The raised serum folate was cited as supporting methylfolate trapping.

These views have been difficult to test as patients with untreated pernicious anaemia do not readily lend themselves to the sort of study required.

The situation was transformed by the observation that the anaesthetic gas nitrous oxide (N₂O) is activated by organometallic complexes of which B₁₂ is the prime example.¹³ N₂O is cleaved and at the same time B₁₂ is oxidised to an irreversibly inert form. N₂O, in fact, specifically inactivates the enzyme methionine synthetase, of which B₁₂ is a coenzyme.¹⁴ Exposure to N₂O rapidly produces "B₁₂ deficiency." In man this can lead to megaloblastic anaemia, neuropathy, and even death. Other species do not become megaloblastic, but some like the monkey and probably fruit bats develop a neuropathy. All, however, develop very similar biochemical changes, and these have now been studied in some depth. It is now possible to assess the validity of the premises on which the methylfolate trap hypothesis was formulated.

1 DOES METHYLFOLATE TRAPPING ACCOUNT FOR THE KNOWN DEFECTS IN B₁₂ DEFICIENCY?

As the methyl group of methylfolate cannot be transferred to homocysteine in B₁₂ deficiency there is impaired use of methylfolate. Thus in the dU suppression test methylfolate did not correct the defect in B₁₂ deficient marrow cells. Neither in marrow cells from pernicious anaemia nor from rats treated with N₂O, however, was tetrahydrofolate itself able to correct the defect in thymidine synthesis, although formylfolate was fully active.³⁵ This is quite an unexpected result from the point of view of the methylfolate trap hypothesis as tetrahydrofolate is outside the trap.

The same pattern of results emerged when the form of folate used by liver for making folate polyglutamate was studied. Normal rat liver used all folate analogues equally for making the polyglutamate. When B₁₂ was inactivated by N₂O, however, no polyglutamate at all was made from methylfolate and tetrahydrofolate, but normal amounts from formylfolate.³⁶ Failure to use tetrahydrofolate and the normal use of formyltetrahydrofolate are not predicted by methylfolate trapping. Rather they suggest a role for B₁₂ in the formation of folate.

2 IS THE IN VITRO PREDICTION THAT METHYLFOLATE CANNOT BE OXIDISED BACK TO METHYLENE AND FORMYLFOLATE CORRECT IN VIVO?

One of the two papers in 1961 that formulated the methylfolate trap theory also contained the seeds for its destruction.⁸ Noronha and Silverman found that 1% methionine added to the diet and fed for 24 hours to rats before sacrifice resulted in a considerable decline in the methyltetrahydrofolate concentrations in liver while increasing the formylfolate and tetrahydrofolate content. This occurred in both control and B₁₂ deficient rats. This implies oxidation of the methyl group to formyl and to carbon dioxide. This has been confirmed many times since. Brody et al.⁵⁷ showed that this occurred within 30 minutes of an injection of...
methionine and that the methyl group oxidation occurred on folate hexaglutamate.

The amount of methionine needed to promote oxidation of the methyl group of methyfolate was as little as 0.5 μmol. S-adenosylmethionine was less active than methionine and seemed to be active only through its further metabolism to methionine. Thus the hepatic concentration of methylfolate is regulated by that of methionine in both normal and B₁₂ deficient animals.

Other observations also point to in vivo oxidation of the methyl moiety of methylfolate. Methylfolate can serve as the methyl donor in the methylation of biogenic amines. The mechanism entails the oxidation of the methyl group to formate, which in turn is transferred to the biogenic amine. The enzyme responsible for the oxidation of the methyl group was the same one concerned with its formation—namely, methylenetetrahydrofolate reductase.

Furthermore, Thorndike and Beck reported that the methyl group of methylfolate was oxidised in an essentially similar manner by lymphocytes from both normoblastic controls and one patient with pernicious anaemia.

3 WHAT IS THE PATHWAY FOR OXIDATION OF THE METHYL GROUP OF METHYLFOLATE IN B₁₂ DEFICIENCY?

Lumb et al. showed that in B₁₂ inactivated rats where the methyl group could not be transferred to homocysteine, methylenetetrahydrofolate itself was used as the substrate for forming methylenetetrahydrofolate. When methylfolate labelled with [¹⁴C] in the methyl group was used [¹⁴C]-labelled polyglutamates containing 3, 4, and 5 glutamic acid residues were identified. As no polyglutamate with the [¹⁴C] label having 6 glutamic acid was present it was concluded that the methyl group was oxidised from the hexaglutamate.

Methionine and cobalamin-folate function

Not only are both folate and cobalamin required for methionine synthesis, but many of the effects of B₁₂ deficiency in both man and rat are overcome to a greater or lesser degree by the provision of methionine.

In man methionine given to patients with pernicious anaemia in relapse will abolish an abnormal urinary formiminoglutamic acid excretion and, used in appropriate dose, will correct the abnormal dU suppression test. In fruit bats treated with N₂O⁴ and in monkeys methionine will considerably improve neuropathy. In B₁₂ inactivated rats methionine will restore to normal folatepolyglutamate synthesis. Even more effective than methionine, is a derivative of methionine via S-adenosylmethionine—namely, 5-methylthioadenosine. This compound is further metabolised to methionine and formate. Methionine can also yield formate by a second pathway—namely, oxidation of its methyl group.

How B₁₂ deficiency affects folate metabolism

Methionine is the pivotal compound in B₁₂ folate metabolism. Lack of B₁₂ produces a shortage of methionine that is only partially alleviated by induction of another pathway to methylation of homocysteine—namely, betaine methyltransferase whereby betaine supplies the methyl group to methylation of homocysteine instead of methylfolate. Lack of methionine has two consequences:

1. Lack of single carbon units at the formate level of oxidation, which arises from both oxidation of the methyl group of methionine and via S-adenosylmethionine → decarboxylated S-adenosylmethionine → 5-methylthioadenosine → 5-methylthioribose → methionine plus formate. Formate is required for purine synthesis and for formation of formyltetrahydrofolate, which seems to be the preferred substrate for folate polyglutamate synthesis, and by further reduction into methylene for pyrimidine synthesis.

2. The lack of S-adenosylmethionine, as indicated, may restrict supply of formate. It may interfere with general transmethylation reactions, although a role for transmethylation in haemopoiesis has still to be shown. There is no fall in S-adenosylmethionine values in the brain in fruit bats treated with N₂O and hence impaired transmethylation in brains is unlikely.

Serine has been widely regarded as the main source of single carbon units largely because it is readily available by synthesis from glucose. B₁₂ inactivation does not affect the pathways by which serine can donate a single carbon unit. Nevertheless, large doses of serine do not in any way ameliorate the effect of B₁₂ inactivation. This must cast doubt on the importance of serine as a major single carbon unit donor.

The hypothesis that has been advanced to explain B₁₂-folate interrelations—the formate-starvation hypothesis—postulates that B₁₂ deficiency leads to shortage of methionine, and this in turn, to a shortage of active-formate derived from methionine.

References


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