More than 50 years ago, Victor Herbert first described the concept that defective nucleoprotein synthesis, attributable to various causes, results in the development of megaloblastic anemia. Megaloblastic anemia is characterized by the presence of a hypercellular marrow with large, abnormal hematopoietic progenitor cells with a characteristic finely stippled, lacy nuclear chromatin pattern. These abnormal progenitor cells, or megaloblasts, were first described by Paul Ehrlich in 1880. Leukopenia and thrombocytopenia are frequently present. Although the marrow is hypercellular, many of the cells die within it in a process called ineffective erythropoiesis. Megaloblastosis usually results from a deficiency of vitamin $B_{12}$ (cobalamin) or folic acid, or a deficiency in their metabolism; however, any interference with the synthesis of purines, pyrimidines, or protein may result in megaloblastosis.

Megaloblastic maturation is the morphologic result of any biochemical defect that causes a slowing of DNA synthesis. The hallmark of this megaloblastosis is nuclear-cytoplasmic dissociation; the nucleus remains immature in appearance while the cytoplasm matures more normally. This dissociation, which is the result of DNA synthesis that is retarded relative to normal RNA and protein synthesis, is manifested in the marrow and other proliferating tissues in the body by large cells containing a large nucleus with a diffuse and immature-appearing chromatin content, surrounded by normal-appearing cytoplasm. However, a high mean corpuscular volume does not necessarily imply a diagnosis of megaloblastic anemia. A high mean corpuscular volume is noted also in cases of alcohol abuse, hypothyroidism, aplastic anemia, myelodysplasia, and any condition in which the reticulocyte count is considerably elevated (such as in hemolytic anemia); it may also be a congenital finding.

Since it was first described in 1849 by Thomas Addison, megaloblastic anemia has been attributed to both congenital (uncommon) and acquired (common) problems. It is most frequently related to vitamin $B_{12}$ deficiency due to defective absorption, folic acid deficiency due to malnutrition, or both. However, because of the correction of most of the dietary causes of vitamin $B_{12}$ and folate deficiency, drug-induced megaloblastic anemia has become a more prominent cause of megaloblastic anemia. The drugs that may cause this condition are commonly used in clinical practice, and their effects on DNA synthesis pathways may be underappreciated (Table 1).

A number of biochemical processes in DNA synthesis are vulnerable to inhibition by drugs, but among the most important of these is the new synthesis of thymidine. Figure 1 shows the structure of nucleotides and their associated terminology. Thymidine is a component of DNA but not RNA, and it is present in cells in rate-limiting amounts. The other nucleotides tend to be present in excess. Thymidine can be salvaged from the turnover of DNA, but the main source is the addition of a methyl group to the 5-position of the pyrimidine ring to convert...
deoxyuridylate to deoxythymidylate (Fig. 2). This methylation process depends crucially on folate and vitamin B₁₂.

Drugs cause megaloblastic anemia by impairing the cellular availability or use of folic acid or vitamin B₁₂. This may occur because of interference with the absorption, plasma transport, or delivery of folate or vitamin B₁₂, competition for reducing enzymes, end-product inhibition of cofactor-mediated reactions, or physical destruction of the vitamins (Fig. 1).²

Small amounts of vitamin B₁₂ are required on a daily basis (1 to 2.5 μg). Because folate food fortification tends to obscure the hematologic consequences of vitamin B₁₂ deficiency, the early effects of drugs that interfere with vitamin B₁₂ may be neurologic complications rather than the development of clinically significant anemia.⁵ These neurologic manifestations can be modest or more dramatic, with the development of myelopathy, neuropathy, optic atrophy, and neuropsychiatric and, rarely, autonomic disturbances such as bladder or erectile dysfunction. A discussion of these neurologic problems and their biochemical basis is beyond the scope of this article, but they have been reviewed in detail by other authors.⁵⁻¹⁰ Clearly, such potentially devastating drug effects underscore the need for the clinician to be alert to them.

### Table 1. Drugs That Cause Megaloblastic Anemia.

<table>
<thead>
<tr>
<th>Mechanism of Action and Agent</th>
<th>Type of Medication or Indication</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Modulates purine metabolism</strong></td>
<td></td>
</tr>
<tr>
<td>Azathioprine</td>
<td>Immunomodulator</td>
</tr>
<tr>
<td>Mycophenolate mofetil</td>
<td>Immunomodulator</td>
</tr>
<tr>
<td>Thioguanine</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Mercaptopurine</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Cladribine</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Fludarabine</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Pentostatin</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Methotrexate</td>
<td>Immunomodulator, antineoplastic agent</td>
</tr>
<tr>
<td>Allopurinol</td>
<td>Xanthine oxidase inhibitor</td>
</tr>
<tr>
<td><strong>Interferes with pyrimidine synthesis</strong></td>
<td></td>
</tr>
<tr>
<td>Cytosine arabinoside</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Gemcitabine</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Capecitabine</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Hydroxyurea</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Methotrexate</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Mercaptopurine</td>
<td>Immunomodulator, antineoplastic agent</td>
</tr>
<tr>
<td>Fluourouracil</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Trimethoprim</td>
<td>Antibacterial agent</td>
</tr>
<tr>
<td>Nitrous oxide</td>
<td>Anesthetic agent</td>
</tr>
<tr>
<td>Gadolinium (paramagnetic metal ion)</td>
<td>Contrast agent in magnetic resonance imaging</td>
</tr>
<tr>
<td>Lefunomide</td>
<td>Immunomodulator in patients with psoriasis or rheumatoid arthritis</td>
</tr>
<tr>
<td>Teriflunomide</td>
<td>Immunomodulator in patients with multiple sclerosis</td>
</tr>
<tr>
<td><strong>Decreases absorption of folic acid</strong></td>
<td></td>
</tr>
<tr>
<td>Alcohol</td>
<td></td>
</tr>
<tr>
<td>Aminosalicylic acid</td>
<td>For tuberculosis and inflammatory bowel disease</td>
</tr>
<tr>
<td>Birth-control pills</td>
<td>Hormones</td>
</tr>
<tr>
<td>Estrogens</td>
<td>Hormones</td>
</tr>
<tr>
<td>Tetracyclines</td>
<td>Antibiotic</td>
</tr>
<tr>
<td>Ampicillin and other penicillins</td>
<td>Antibiotic</td>
</tr>
<tr>
<td>Chloramphenicol</td>
<td>Antibiotic</td>
</tr>
<tr>
<td>Nitrofurantoin</td>
<td>Urinary antiseptic</td>
</tr>
<tr>
<td>Erythromycin</td>
<td>Antibiotic</td>
</tr>
</tbody>
</table>

**DRUGS THAT ALTER PURINE METABOLISM, PYRIMIDINE METABOLISM, OR BOTH**

In both purine and pyrimidine synthesis (Fig. 2), the methyl group is donated by 5,10-methylene tetrahydrofolate. The consequences of inhibition of pyrimidine synthesis are more dangerous to the cell than inhibition of purine synthesis. Thymidylate synthase converts deoxyuridylate to thymidylate by transferring the methyl group from methylene tetrahydrofolate, and in the process it yields dihydrofolate.

In order for the thymidylate synthase reaction to continue, the folate must reacquire a methyl group to donate. The first step is to regenerate tetrahydrofolate from dihydrofolate. This is accomplished through the action of dihydrofolate reductase. Tetrahydrofolate is then converted to 5,10-methylene tetrahydrofolate through the ac-

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Incidentally, the table below identifies the drugs that can alter purine metabolism, pyrimidine metabolism, or both.
Drug-Induced Megaloblastic Anemia

Serine hydroxymethyltransferase, if dihydrofolate is not reduced and methylated, the cell is starved of thymidylate, and DNA synthesis slows. This is crucial role of dihydrofolate reductase in thymidine nucleotide biosynthesis that makes it a target for antineoplastic therapy. This pathway is also targeted in antibacterial therapy, especially by sulfa drugs.

Purine and pyrimidine antagonists or analogues are commonly used in the treatment of cancers, as immune antagonists, and as antiviral agents. Inhibitors of thymidylate synthase are called suicide substrates because they irreversibly inhibit the enzyme. Molecules of this class include fluorouracil and 5-fluorodeoxyuridine. Both are converted within cells to 5-fluorodeoxyuridylate, which then inhibits thymidylate synthase.

Antimetabolites, which masquerade as a purine or a pyrimidine, inhibit DNA synthesis by preventing these substances from becoming incorporated into DNA during the S phase of the cell cycle. Purine synthesis inhibitors include a number of commonly used drugs: aminopterin, an immunosuppressant agent used in organ transplantation, autoimmune disorders, and inflammatory bowel disease; methotrexate, a direct inhibitor of dihydrofolate reductase that indirectly inhibits purine synthesis by blocking the metabolism of folic acid; and allopurinol, which is used to treat hyperuricemia because it inhibits the enzyme xanthine oxidoreductase.

Pyrimidine synthesis inhibitors are also used in active moderate-to-severe rheumatoid arthritis and psoriatic arthritis. For example, leflunomide inhibits T-cell responses and induces a shift of CD4 T cells from the type 1 helper T (Th1) cell (proinflammatory) to type 2 helper T (Th2) cell subpopulation. This process results in a beneficial effect in diseases in which T cells play a major role in the initiation and propagation of inflammation. Both leflunomide and its metabolite teriflunomide, which is approved for use in multiple sclerosis, inhibit dihydroorotate dehydrogenase.

### Table 1. (Continued.)

<table>
<thead>
<tr>
<th>Mechanism of Action and Agent</th>
<th>Type of Medication or Indication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aminopterin</td>
<td>Antineoplastic agent,</td>
</tr>
<tr>
<td></td>
<td>immunosuppressive agent</td>
</tr>
<tr>
<td>Phenobarbital</td>
<td>Antiseizure agent</td>
</tr>
<tr>
<td>Phenytoin</td>
<td>Antiseizure agent</td>
</tr>
<tr>
<td>Quinine</td>
<td>Antimalarial agent</td>
</tr>
<tr>
<td>Chloroquine</td>
<td>Antimalarial agent</td>
</tr>
<tr>
<td>Primaquine</td>
<td>Antimalarial agent</td>
</tr>
<tr>
<td>Artemether lumefantrine</td>
<td>Antimalarial agent</td>
</tr>
<tr>
<td>Sulfadoxine–pyrimethamine</td>
<td>Antimalarial agent</td>
</tr>
<tr>
<td>Glutethimide</td>
<td>Hypnotic sedative</td>
</tr>
<tr>
<td>Has folate analogue activity</td>
<td></td>
</tr>
<tr>
<td>Methotrexate</td>
<td>Immunomodulator,</td>
</tr>
<tr>
<td></td>
<td>antineoplastic agent</td>
</tr>
<tr>
<td>Pemetrexed</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Raltitrexed</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Proguanil</td>
<td>Antineoplastic agent</td>
</tr>
<tr>
<td>Pyrimethamine</td>
<td>Antimalarial agent</td>
</tr>
<tr>
<td>Trimethoprim</td>
<td>Antibacterial agent</td>
</tr>
<tr>
<td>Decreases absorption of vitamin B₁₂</td>
<td></td>
</tr>
<tr>
<td>Cycloserine</td>
<td>For tuberculosis and</td>
</tr>
<tr>
<td></td>
<td>psychiatric conditions</td>
</tr>
<tr>
<td>Isoniazid</td>
<td>For tuberculosis</td>
</tr>
<tr>
<td>Metformin</td>
<td>For diabetes and prediabetes</td>
</tr>
<tr>
<td>Aminosalicylic acid</td>
<td>For tuberculosis and</td>
</tr>
<tr>
<td></td>
<td>inflammatory bowel disease</td>
</tr>
<tr>
<td>Colchicine</td>
<td>For gout, familial Mediterranean</td>
</tr>
<tr>
<td></td>
<td>fever, and Behçet’s disease</td>
</tr>
<tr>
<td>Neomycin</td>
<td>Antibiotic</td>
</tr>
<tr>
<td>Histamine₂-receptor antagonists (H₂ blockers)</td>
<td></td>
</tr>
<tr>
<td>Proton-pump inhibitors</td>
<td></td>
</tr>
<tr>
<td>Increases excretion of vitamin B₁₂</td>
<td></td>
</tr>
<tr>
<td>Sodium nitroprusside</td>
<td></td>
</tr>
<tr>
<td>Destroys vitamin B₁₂</td>
<td></td>
</tr>
<tr>
<td>Nitric oxide</td>
<td></td>
</tr>
<tr>
<td>Has unknown mechanism</td>
<td></td>
</tr>
<tr>
<td>Arsenic</td>
<td></td>
</tr>
<tr>
<td>Benzene</td>
<td></td>
</tr>
<tr>
<td>Sulfasalazine</td>
<td></td>
</tr>
<tr>
<td>Asparaginase</td>
<td></td>
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</tbody>
</table>
Nitrous oxide, an anesthetic gas that has become increasingly popular for use as a recreational drug, may cause megaloblastic anemia by blocking the conversion of vitamin B₁₂ from the reduced to the oxidized form. In the cytoplasm, methionine synthase requires the reduced form of vitamin B₁₂ (methylcobalamin) to convert homocysteine to methionine. In contrast, in the mitochondria, the oxidized form of vitamin B₁₂ (5′-deoxyadenosylcobalamin) converts methylmalonyl–coenzyme A (CoA) to succinyl CoA. Thus, in the mitochondria, nitrous oxide will inhibit the activity of methylmalonyl CoA mutase, leading to the impairment of methylation reactions and DNA synthesis.¹⁶⁻¹⁹

Inhibitors of Ribonucleotide Reductase

Although they are not as ubiquitous as drugs that interfere with DNA synthesis, cytosine arabinoside, hydroxyurea, and gemcitabine inhibit the function of ribonucleotide reductase. This inhibition blocks the conversion of cytidine diphosphate or triphosphate to its corresponding deoxyribonucleotides. Cytosine arabinoside — once it is rapidly phosphorylated to its active metabolite, 5-triphosphate cytosine arabinoside — inhibits DNA polymerase. After its incorporation into DNA or RNA, it may also inhibit RNA polymerase.

DRUGS THAT INTERFERE WITH ABSORPTION OF FOLIC ACID

Folic acid (pteroylglutamic acid) cannot be synthesized in humans, so it must be obtained in the diet, where its major sources are green leafy vegetables, citrus fruits, liver, and whole grains. Dietary folates (5-methyltetrahydrofolate and formyltetrahydrofolate) are readily transported across the intestinal membranes. Vitamin B₁₂–dependent methionine synthetase converts 5-methyltetrahydrofolate to tetrahydrofolate, the form of folate that is required for nucleotide biosynthesis.

Methylenetetrahydrofolate is required for the conversion of methionine to S-adenosylmethionine (SAM). Thus, when folate levels are low, SAM is depleted, resulting in a reduction in the methylation of cytosine in DNA. The consequences of this reduced DNA methylation include enhanced gene transcription and DNA strand breaks; these are key factors leading to many adverse effects, including the possibility of malignant transformation.

Conversely, since folate acts as a cofactor that is regenerated in a cyclic manner, any drug that...
blocks the completion of this cycle (Fig. 2) will result in the accumulation of one of the metabolites of the vitamin in an unusable form, giving rise to a megaloblastic anemia. In this way, vitamin B₁₂ deficiency leads to an accumulation of 5-methyltetrahydrofolate, which leads to megaloblastosis that is, on a peripheral-blood smear, indistinguishable from that associated with folic acid deficiency. The interrelationship of folic acid and vitamin B₁₂ metabolism in this cyclical pathway is informative in determining the treatment that is required to correct the problem of either folic acid or B₁₂ deficiency.¹⁰

Thus, any drug that interferes with the intracellular concentration of folic acid, its intracellular conversion to its appropriate metabolites, or both can lead to megaloblastic anemia. Drugs may cause a perturbation in the intracellular concentration by decreasing intestinal absorption, decreasing transport and delivery to cells, decreasing transport across cell membranes, decreasing cellular retention (which includes increased excretion), increasing destruction, and increasing the requirement for folic acid. Some drugs affect the conversion or use of folic acid by interfering with the availability of vitamin B₁₂ or interfering with the enzymes involved in the conversion of folic acid to its appropriate metabolites.²⁻⁵,¹⁰⁻²¹

Many drugs interfere with the absorption or proper distribution of folic acid. These include alcohol, antiseizure agents, contraceptive drugs, and antibiotics (Table 1).

Alcohol is associated with the development of megaloblastic anemia because of a low-folate diet in persons with alcoholism and because of an inhibition of intestinal absorption, metabolic use, and hepatic uptake and storage of folate.²²,²³ Alcohol is not thought to act through the dihydrofolate reductase pathway. Rather, the likely effect of alcohol is on the intestinal mucosa, where it can interfere with both vitamin B₁₂ and folate absorption. The effect on vitamin B₁₂ absorption may be due to direct toxic effects on the gastric mucosa that cause interference with the production of intrinsic factor.²² Ethanol also has a direct effect on the maturation of hematopoietic progenitor cells in the marrow. This effect may be due to the inhibition of a specific enzyme, 10-formyl-tetrahydrofolate dehydrogenase, as shown in studies in animals.²⁴

The mechanism by which folate absorption is affected by the use of oral contraceptives remains controversial. The use of contraceptives results in a partial inhibition of intestinal deconjugation of polyglutamyl forms of folic acid.²⁵,²⁶ This may explain why folic acid levels are usually normal in women who receive contraceptives, and it implies that absorption remains

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**Figure 2. The Synthesis of Thymidylate, the DNA Nucleotide That Is a Rate-Limiting Factor in the Synthesis of DNA.**

Both folic acid and vitamin B₁₂ play a critical role as cofactors in the pathway that leads to the synthesis of thymidylate. Folate is absorbed in the small intestine mainly as 5-methyltetrahydrofolate. Once it enters the cell, it is demethylated to form tetrahydrofolate in a vitamin B₁₂–dependent enzymatic step that generates methionine from homocysteine. Homocysteine levels are increased in cobalamin deficiency because of the inhibition of this conversion. The tetrahydrofolate is then remethylated in a reaction in which serine donates a methyl group and pyridoxine (vitamin B₆) is a cofactor. The product is 5,10-methylene tetrahydrofolate. That methyl group is subsequently added to the 5-carbon of uridylate to form thymidylate (thymidine monophosphate). As a consequence of donating the methyl group, 5,10-methylene tetrahydrofolate becomes dihydrofolate. Dihydrofolate is then reduced by dihydrofolate reductase to generate tetrahydrofolate. Fluorouracil blocks thymidylate synthase. Methotrexate blocks dihydrofolate reductase.
adequate until some additional clinically important problem with absorption or dietary deficiency is superimposed on the use of the contraceptive.

Phenytoin and other anticonvulsant agents have also been associated with the development of megaloblastic anemia. However, a key difference between women who use birth-control pills and persons who receive phenytoin and other antiseizure medications is that folate levels are noted to be low in people who receive phenytoin. Phenytoin does not seem to have any effect on the folate metabolism pathways, nor does it appear to affect the excretion of folate. However, most antiseizure medications increase hepatic microsomal enzyme activity, and it is believed that this increase in activity may result in an increase in the use of folic acid, thus leading to a decrease in serum folate levels. Similarly, antiseizure drugs may enhance hepatic detoxification enzymes, thus causing an increased breakdown of folic acid.

Antiseizure medications are also associated with a considerable decrease in the intestinal absorption of folic acid. Folate uses an active transport mechanism in the intestinal mucosa, as evidenced by the fact that some forms of folate, such as methyltetrahydrofolate, are absorbed more readily than others. However, since the various antiseizure medications are distinctly different from one another, it is unlikely that all these drugs would have a similar direct effect on the intestinal mucosa that would result in a decrease in active absorption of folic acid. Rather, it would appear that the effect is through a secondary action such as “solvent drag” (movement of folate across the cell membrane by bulk transport following the movement of water rather than being facilitated by ion channels or cellular pumps), sodium exchange, or an effect on intestinal ATPase. Again, the probable reason that anticonvulsants are not a more common cause of megaloblastic anemia is that the gastrointestinal tract has a vast excess capacity for the absorption of important nutrients such as folic acid. Thus, some added compromise to absorption or significant diminution in the intake of folic acid is necessary for anemia to become an overt problem in patients. The addition of more folic acid to the patient’s diet will probably prevent or correct the problem.

Folate transport in the blood is facilitated by a carrier protein. Aspirin may reduce the binding of folate to its serum protein carrier. Similarly, phenytoin and other anticonvulsants that bear structural resemblances to folate may cause a decrease in serum folate levels by reducing the transport of folate. Finally, and again because of the structural similarities between anticonvulsants and folic acid, the therapeutic effects of some of these drugs have been thought to be due partially to their folate analogue activities. Of note, phenytoin and other anticonvulsants have been noted to cause immunosuppression and even myelosuppression. In addition, administration of folate in persons with seizures has been reported to increase the incidence of seizures in those persons, whereas low folate states have been associated with improved seizure control.

**DRUGS THAT INTERFERE WITH THE METABOLISM OF FOLIC ACID**

Drugs that are commonly termed folate analogues lead to a break in the important cyclic pathway in which folic acid is critically involved in returning dihydrofolate to tetrahydrofolate (Fig. 1). Many folate analogues have been synthesized for a variety of therapeutic purposes. Most commonly, they are used in the treatment of malignant diseases such as leukemia, as well as various solid tumors, including lung, bladder, breast, and head and neck cancers, mesothelioma, and sarcomas. Common to each of these drugs is the ability to bind to the enzyme dihydrofolate reductase, thus inhibiting the reduction of dihydrofolate to tetrahydrofolate. In this way, a true deficiency of reduced folic acid (i.e., a deoxidized form of folic acid caused by dihydrofolate reductase in the metabolism of dihydrofolate to tetrahydrofolate, which involves the use of NADPH as an electron donor) is produced.

Clinically, this folate analogue–generated defect can be corrected by administration of reduced folic acid in the form of folic acid (10-formyl-tetrahydrofolate), since the reduced folic acid is beyond the block to the pathway caused by the folate analogue. The use of folic acid should be considered prophylactically in patients who receive high doses of methotrexate. Folinic acid therapy should be initiated 24 hours after the administration of methotrexate in order to offset the adverse effects of methotrexate.
on the more rapidly dividing progenitor cells of
the gastrointestinal tract and bone marrow.

Pemetrexed, a folate analogue that inhibits
multiple enzymes involved in purine and py-
rimidine synthesis (thymidylate synthetase,
dihydrofolate reductase, glycaminide ribonucleo-
tide formyltransferase, and 5-aminoimidazole-
4-carboxamide), is commonly used in the
treatment of various solid tumors, including
mesothelioma, lung, colon, breast, and head and
neck cancers. The use of folic acid can amelio-
rate the toxic effects of pemetrexed without di-
minishing its efficacy.28-30

Other uses of folate analogues are based on
the fact that the dihydrofolate reductase of vari-
ses species shows varying affinities for folate
antagonists. Thus, a folate analogue, such as
trimethoprim, was developed to treat various
bacterial infections, and pyrimethamine was
developed to treat protozoan infections.31

Trimethoprim is a structurally remote ana-
logue of folic acid. It was developed because of
biochemical evidence that its structural altera-
tions produce a compound that maximally binds
to the bacterial form of dihydrofolate reductase
with minimal binding to the mammalian en-
zyme. Trimethoprim binds to a different dihy-
drofolate reductase epitope than methotrexate
and interferes with the human enzyme only
under unusual circumstances (e.g., in the case of
human immunodeficiency virus infection when
other DNA synthesis inhibitors are also used).31

Trimethoprim and pyrimethamine are often
combined with sulfonamides. Sulfonamide is an
antagonist of para-aminobenzoic acid, a folate
precursor in microorganisms, but not in hu-
mans.31 Megaloblastic changes may develop in
patients receiving trimethoprim and pyrimetha-
mime because of the inhibition of DNA synthesis.
Folinic acid completely reverses this effect with-
out interfering with the antibacterial properties
of the drugs.

**DRUGS THAT DECREASE
THE ABSORPTION OF VITAMIN B\textsubscript{12}\**

The absorption of vitamin B\textsubscript{12} from food is shown
in Figure 3. Animal products (meat, fish, chicken,
and dairy products) are the only natural source
of vitamin B\textsubscript{12} (cobalamin), which is synthesized
in bacteria. Cobalamin is a coenzyme in the in-
teractions of only two enzymes in mammals.

One of them, methylmalonyl-CoA mutase, is im-
portant in the catabolism of fatty acids in mito-
chondria; the other is methionine synthetase.10

After ingestion, cobalamin is bound to haptoc-
corrin, a glycoprotein related to plasma transco-
balamin I, a member of the cobalamin-binding
protein family, which is present in the saliva and
other gastrointestinal juices. Haptocorrin is de-
graded by gastric enzymes and acid, after which
the released cobalamin binds to intrinsic factor.
This reaction is favored by an alkaline pH.10

In the terminal ileum, intrinsic factor attaches
to a receptor, cubilin, which is located on the
microvillus membrane and facilitates receptor-
mediated transport of cobalamin in a neutral pH
environment with the presence of calcium ions.
Cubilin regeneration requires the presence of a
protein, amnionless, and is thought to require
a second protein, megalin, which stabilizes the
cubilin-amnionless complex. In the process of
cobalamin transport into ileal cells, intrinsic fac-
tor is degraded by lysosomal enzymes, and the
free cobalamin in the plasma becomes bound to
one of two major cobalamin-binding proteins,
either transcobalamin I or transcobalamin II.10

This transcobalamin–cobalamin complex is
transported across cellular membranes in the
liver and other organs by two related receptors
that belong to the low-density lipoprotein–recep-
tor gene family, CD320 and renal Lrp2, or mega-
lin.32-34 It is also filtered in the kidney, where the
major portion is excreted, while some is reab-
sorbed by kidney cells and is secreted back into
the plasma.

Drugs that interfere with B\textsubscript{12} absorption in-
clude aminosalicylic acid, colchicine, neomycin,
and metformin.35,36 Because of the minute amount
of B\textsubscript{12} required by the body and its abundance in
most diets, it is relatively rare that these agents
may give rise to megaloblastic anemia. In most
instances, the impaired absorption is believed to
be secondary to an effect of the drug on the in-
testinal mucosa of the terminal ileum, where
vitamin B\textsubscript{12} is absorbed. There are no reports of
these drugs causing intrinsic-factor abnormali-
ties or other problems with regard to the trans-
port of vitamin B\textsubscript{12} across membranes and in the
circulation.35 The effect of metformin on vitamin
B\textsubscript{12} absorption is reversible with calcium because
the ileal absorption of vitamin B\textsubscript{12}, as indicated
previously, is a calcium-dependent process.37

Another factor that may play a role in the

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intestinal absorption of vitamin B₁₂ is an alteration in the intestinal pH. Since vitamin B₁₂ is a weak acid, its absorption is decreased in an alkaline environment. Phenytoin in solution has a very high pH (approximately 12), and an elevated gastric pH has been noted in persons who have been receiving long-standing phenytoin therapy. This may partially explain why antacids such as histamine₂-receptor antagonists (H₂ blockers) and proton-pump inhibitors may, on rare occa-
that folate and vitamin B12 intake are adequate. No acceptable alternatives, one should ensure that folate and vitamin B12 intake are adequate. If the causative drug is excluded from the therapeutic regimen or, when possible, bypassing the antagonism with folinic acid.

Perhaps a more consequential complication of vitamin B12 and folate deficiency is the resultant hyperhomocysteinemia. Homocysteine is a neurotoxic amino acid that is not found in proteins. An elevated homocysteine level has been implicated in many pathologic conditions, including cardiovascular diseases, fetal neural-tube defects, and, perhaps more questionably, in several neurodegenerative disorders such as stroke, Parkinson’s disease, and Alzheimer’s disease. Elimination of homocysteine is regulated by both the transmethylation and transsulfuration pathways and is thus affected by folate, whereas the conversion of homocysteine to methionine is mediated by methionine synthase, the activity of which is regulated through vitamin B12. Homocysteine also seems to play an important role in the regulation of neurogenesis and apoptosis.

Other effects of folate and vitamin B12 deficiency are related to the fact that they play key roles as methyl donors in one-carbon metabolism. The results of methyl-donor deficiency have been noted in studies of intrauterine growth retardation. In addition, reduced Stat3 signaling targeted by miR-124 has been associated with long-term postnatal brain defects. Even depression may be affected by folate deficiency owing to effects on the synthesis of neurotransmitters such as monoamine metabolites.

Thus, the consequences of drug-induced changes in folate and vitamin B12 physiology can be substantial. Early recognition is critical for the prevention of irreversible consequences.

Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

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