Lower levels of dietary folate are associated with the development of epithelial cell tumours in man, particularly colo-rectal cancer. In the majority of epidemiological studies blood folate or reported folate intake have been shown to be inversely related to colo-rectal cancer risk. Folate, via its pivotal role in C1 metabolism, is crucial both for DNA synthesis and repair, and for DNA methylation. This function is compromised when vitamin B12 is low. Vitamin B12 deficiency has been shown to increase biomarkers of DNA damage in man but there is no evidence directly linking low vitamin B12 with cancer. Disturbingly, folate and vitamin B12 deficiencies are common in the general population, particularly in the underprivileged and the elderly. How folate and/or vitamin B12 deficiency influence carcinogenesis remains to be established, but it is currently believed that they may act to decrease DNA methylation, resulting in proto-oncogene activation, and/or to induce instability in the DNA molecule via a futile cycle of uracil misincorporation and removal. The relative importance of these two pathways may become clear by determining both DNA stability and cytosine methylation in individuals with different polymorphic variants of key folate-metabolising enzymes. 5,10-Methylenetetrahydrofolate reductase converts 5,10-methylenetetrahydrofolate to 5-methyltetrahydrofolate and thereby controls whether folate is employed for DNA synthesis or DNA methylation. Colo-rectal cancer risk is decreased in subjects homozygous for a common variant (C677T) of the gene coding for this enzyme, suggesting that DNA synthesis and repair may be ‘enhanced’ in these individuals. Evidence from animal and human studies is presented here in support of folate acting to maintain genomic stability through both these mechanisms.

Folate: Vitamin B12: DNA stability: DNA methylation: MTHFR: Colon cancer

Folate and colo-rectal cancer risk

Inadequate dietary folate has been implicated in the development of several epithelial-cell cancers, including cancer of the cervix, lung and breast (Glynn & Albanes, 1994). However, the most convincing evidence linking low folate intake with an increased risk of malignancy relates to colo-rectal cancer (Prinz-Langenohl et al. 2001; Giovannucci, 2002; Potter, 2002). Cohort and case-control studies have consistently shown an inverse relationship between colo-rectal cancer incidence, reported intake of folate and blood-cell folate concentrations (Benito et al. 1991; Giovannucci et al. 1995; Giovannucci, 2002; Konings et al. 2002; Potter, 2002). Plasma and erythrocyte folate levels are lower in colo-rectal cancer patients than in normal subjects (Porcelli et al. 1996). Conversely, supplementation with folic acid protects against the development of colo-rectal neoplasia in high-risk patients with ulcerative colitis (Lashner et al. 1997).

Folate, vitamin B12 and genomic stability

Folate has a fundamental role in DNA metabolism and function through its ability to methylate cytosine and regulate gene expression, and via its role in nucleotide synthesis and DNA repair (Fig. 1). It is currently believed that folate deficiency may increase the risk of malignant transformation by disrupting both these functions. 5-Methyltetrahydrofolate, the major circulating form of folate, acts as a cofactor in the conversion of homocysteine to methionine. Methionine is subsequently metabolised to S-adenosylmethionine, the principal methyl donor in the majority of biochemical reactions, including cytosine...

Abbreviation: MTHFR, 5,10-methylenetetrahydrofolate reductase.
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methylation in DNA. DNA methylation controls gene expression. Under conditions of folate deficiency S-adenosylmethionine is depleted and S-adenosylhomocysteine the product of methyltransferase activity is elevated, leading to DNA hypomethylation (Yi et al. 2000), inappropriate proto-oncogene activation and transcription, and malignant transformation (Feinberg & Vogelstein, 1983; Fang et al. 1996; Fang & Xiao, 2001).

Folic acid is essential for the synthesis of purines and the pyrimidine nucleoside thymidine. dUMP is converted to TMP by thymidylate synthase using 5,10-methylene tetrahydrofolate as a methyl donor. If folate is low dUMP may accumulate, inducing uracil misincorporation into DNA in place of thymine. DNA repair enzymes act to remove misincorporated uracil from the DNA strand, causing a temporary breakage in the DNA molecule that is sealed by DNA ligase. However, if folate is continually limited, uracil misincorporation and repair may occur repeatedly in a ‘catastrophic’ or ‘futile’ repair cycle causing frequent breakage of the DNA molecule, chromosomal damage and malignant transformation (Reidy, 1987; Blount & Ames, 1994). Moreover, purine biosynthesis is negatively affected by low folate (10-formyltetrahydrofolate), similarly reducing the availability of nucleotides for DNA synthesis and repair (Fig. 1).

A deficiency in vitamin B₁₂ would be expected to induce DNA instability in the same way as folate deficiency. Both 5-methyltetrahydrofolate and vitamin B₁₂ are required for the methylation of homocysteine to methionine by methionine synthase (Fig. 1). When vitamin B₁₂ is limiting 5-methyltetrahydrofolate is not metabolised to tetrahydrofolate, which in turns reduces the availability of 5,10-methylene tetrahydrofolate in the methylation of dUMP to dTMP for DNA synthesis and repair. Similarly, failure of 5-methyltetrahydrofolate to act in the remethylation of homocysteine to methionine limits the production of S-adenosylmethionine, which in turn may result in DNA hypomethylation and proto-oncogene activation. While there is no direct evidence linking vitamin B₁₂ deficiency with genomic instability in human cells in vitro (Fenech, 2001a), vitamin B₁₂ deficiency does increase DNA damage in man. Endogenous micronuclei frequency (as an indicator of chromosomal damage) is negatively associated with serum vitamin B₁₂ (Fenech, 1997), and can be markedly reduced by vitamin B₁₂ supplementation (Fenech et al. 1998). Although the geno-protective effect of vitamin B₁₂ in these studies is reported to act independently of folate (Fenech, 1997; Fenech et al. 1998), there is little evidence of a relationship between vitamin B₁₂ and cancer, and this issue will not be discussed further.

Data from in vitro experiments and in vivo rodent and human studies support the theory that folate (and where appropriate vitamin B₁₂) deficiency can act to induce genomic instability and carcinogenesis. This proposition is discussed in the remainder of the present review.

### Folate deficiency and altered DNA methylation

Methylation of genes at specific locations in the DNA molecule either stops or reduces the rate of transcription. In this way site-specific DNA methylation controls gene expression and function. Alterations or disruption either to global or site-specific DNA methylation may increase malignant transformation. Changes in S-adenosylmethionine:S-adenosylhomocysteine ratio and subsequent global DNA hypomethylation are associated with tumour progression and multiplicity in the Min mouse model of colon
cancer (Sibani et al. 2002). Aberrant DNA methylation is one of the most common molecular changes in human cancers. Global DNA hypomethylation is frequently found in human tumours and is an early event in carcinogenesis, while hypermethylation of the promoter region of certain tumour suppressor genes may accelerate the carcinogenic process (Fang & Xiao, 2001; Johanning et al. 2002).

It has long been established that extreme methyl depletion alters genomic methylation. For example, global genomic DNA hypomethylation is induced in rats fed a methyl-deficient diet (deficient in methionine, choline, folic acid and vitamin B12), and mRNA for the specific proto-oncogenes c-myc, c-fos and c-Ha-ras is elevated (Wainfain & Poirier, 1992). However, the effect of folate deficiency alone on DNA methylation varies markedly according to the tissue under investigation, the rodent model and the treatment regimen employed. Rats fed a folate-depleted diet for 4 weeks exhibit hypomethylated DNA in the liver (Balaghi & Wagner, 1993), while folate deficiency appears specifically to favour hypomethylation of p53 exons 6 and 7 from rat colon mucosa. Moreover, folate supplementation can reverse chemically-induced hypomethylation in exon 8 of the p53 proto-oncogene (Kim et al. 1996). However, two studies in rats have reported that folate deficiency does not induce hypomethylation, either in total cellular DNA or site-specific methylation in hepatic c-myc or colonic p53 (promoter and exon 6–7; Kim et al. 1995; Sohn et al. 2003), even though colonic mucosal folate concentrations are markedly depleted (Sohn et al. 2003). Additionally, in rats the methylation of hepatic, blood and colonocyte DNA-cytosine is not influenced by folate status (Duthie et al. 2000c).

The evidence demonstrating a role for folate deficiency in the modulation of either global or gene-specific DNA methylation in man is equally inconsistent. DNA hypomethylation (measured in colon tissue) and low folate status are associated with an increased risk of colo-rectal neoplasia (Pufulete et al. 2003a). Few studies have measured DNA methylation in normal colo-rectal mucosa, although a recent study suggests that genomic DNA methylation in this tissue is inversely associated with folate status (Pufulete et al. 2003b). DNA hypomethylation is induced in lymphocytes isolated from healthy post-menopausal women with subclinical folate deficiency (mean plasma folate 9.3 nmol/l compared with 19.5 nmol/l at baseline) following supplementation with folic acid at 56 μg/d for 5 weeks and 111 μg/d for 4 weeks, and is reversible following intervention with folate at 286–516 μg/d (Jacob et al. 1998). These effects on methylation have been confirmed in a study of elderly women consuming a moderately-folate-depleted diet (Rampersaud et al. 2000). In contrast, in subjects with normal folate status, lymphocyte genomic DNA methylation is unaffected by folate status, and supplementation with folate does not alter methylation status (Fenech et al. 1998). This finding has been confirmed in a recent placebo-controlled study in which healthy subjects were supplemented with folic acid (1-2 mg/d) for 12 weeks (GB Basten, MH Hill, N Vaughan, SJ Duthie and HJ Powers, unpublished results). Global DNA methylation remains unchanged throughout the study period (Fig. 2).

Gene-specific DNA hypermethylation occurs during tumour development (Jones & Laird, 1999). A recent in vitro study to determine the impact of folate deficiency on global gene expression in a human naso-pharyngeal carcinoma cell line (KB) has shown that mRNA from only eight genes (sampled from >2000) are altered by folate deficiency, with three genes being up regulated and five genes being down regulated (Jhaveri et al. 2001). DNA from one of the down-regulated genes, H-cadherin, a protein that maintains cell-to-cell adhesion and tissue structure, is hypermethylated. Dysfunction of H-cadherin has been implicated in tumorigenesis (Takeichi, 1993). Folate and methyl deficiencies also increase site-specific DNA methylation (hypermethylation) within the p53 gene in rat liver (Pogribny et al. 1995) and de novo methylation of the p16 tumour suppressor gene promoter (Pogribny & James, 2002). Hypermethylation of p16 is an early pre-neoplastic event that precedes tumorigenesis (Pogribny & James, 2002).

While an increased risk for cancer might be explained by DNA hypermethylation with subsequent silencing of tumour suppressor genes (Esteller et al. 1999), the role of low folate levels in this mechanism is still unclear.

Folate deficiency, DNA synthesis and repair

In vitro, folate deficiency negatively affects intracellular DNA nucleotide precursor pools (James et al. 1994) and dose-dependently increases uracil misincorporation, chromosomal breakage (measured as micronuclei frequency) and chromosomal abnormalities in human lymphocytes (Duthie & Hawdon, 1998; Crott et al. 2001a). Moreover, proliferation is abnormal in these cells and they are unable to repair oxidative DNA damage efficiently (Duthie & Hawdon, 1998). Similar detrimental effects (increased DNA strand breakage, uracil misincorporation and altered DNA base excision repair) are observed in immortalised human colonocytes grown under folate-deficient conditions (Duthie et al. 2000b). Folate deficiency has also been
Folate, colorectal cancer and genetic susceptibility

It had been anticipated that the relative importance of the two previously mentioned mechanisms in the aetiology of folate deficiency and malignant transformation would become apparent by determining DNA stability and cytosine methylation in individuals with specific polymorphisms in critical folate-metabolising genes. Methylenetetrahydrofolate reductase (MTHFR) is an important regulatory enzyme in the metabolism of folate. MTHFR converts 5,10-methylenetetrahydrofolate irreversibly to 5-methyltetrahydrofolate, the principal circulating form of folate and the methyl donor in the remethylation of homocysteine to methionine. This key protein, therefore, controls whether folate is employed for DNA synthesis or DNA methylation. The most common variant of the MTHFR gene is located at nucleotide 677 (C677T) and causes a valine for alanine substitution in the protein that is associated with increased thermal stability and decreased enzyme activity (Frostell et al. 1995). Heterozygotes (CT) or homozygotes (TT) have a markedly reduced in vitro enzyme activity (65 and 30% of the wild type (CC) respectively; Frostell et al. 1995). Homozygosity is associated with changes in the normal distribution of blood folates and homocysteine.

Evidence is now emerging as to how DNA stability and carcinogenesis are affected by polymorphisms in the MTHFR gene. Impaired MTHFR activity might be expected to increase cancer risk as a result of reduced 5-methyltetrahydrofolate levels, with associated DNA hypomethylation and proto-oncogene activation (Fig. 3). However,

![Fig. 3. Schematic diagram highlighting the pivotal role that the 5,10-methylenetetrahydrofolate reductase (MTHFR) protein plays in genomic stability and the potential imbalance that polymorphisms in the gene may cause. (a) Thymidine synthesis; (b) purine synthesis; (c) DNA methylation. THF, tetrahydrofolate; HCY, homocysteine; SAM, S-adenosylmethionine; SAH, S-adenosylhomocysteine.](https://www.cambridge.org/core/terms)
homozgyosity for the C677T variant is actually associated, at least in the majority of studies, with a decrease in colorectal cancer risk (Chen et al. 1996; Ma et al. 1997; Sharp & Little, 2004). Individuals homozygous for the variant (TT) generally have a reduced risk of developing colorectal cancer compared with heterozygotes or wild type (the relative risks are generally in the range 0.45–0.9), at least in subjects with normal plasma folate levels (Sharp & Little, 2004). The relationship between MTHFR genotype and risk of colon cancer appears to be profoundly influenced by diet and environment, with low folate and methyl donor status and high alcohol intake (which adversely affects folate metabolism) either negating the inverse association or increasing risk (Sharp & Little, 2004).

The discovery that this polymorphism in the MTHFR gene in fact decreases colon cancer risk is surprising, given that impaired MTHFR enzyme activity and low blood folate would, based on current epidemiological evidence, be expected to increase risk of malignancy. However, low MTHFR activity may increase plasma 5,10-methylene-tetrahydrofolate, which as discussed earlier is crucial in the production of thymidine and purines for DNA synthesis and repair, and thereby may actually enhance DNA stability by preventing uracil misincorporation and chromosomal breakage (Fig. 3).

Data on the influence of the MTHFR C677T polymorphism on global or site-specific DNA methylation status is inconsistent. Global DNA methylation is influenced in lymphocytes isolated from approximately 200 healthy subjects is similar for all genotypes, and independent of folate status (Narayanan et al. 2004). In contrast, global DNA hypomethylation has been reported in leucocytes from nine TT individuals compared with ten subjects with the CC genotype (Choi et al. 1999; Stern et al. 2000), yet methylation at exon 5–8 of the p53 gene is similar for all variants (Choi et al. 1999). The results of a larger study have shown that genomic DNA methylation in peripheral blood mononuclear cells is lower in TT compared with CC individuals when plasma folate concentrations are low (Friso et al. 2002). 5-Methylcytosine levels are lower in normal human colon, breast and lung tissue from CT and TT individuals (Paz et al. 2002). Contrary to expectations, this relationship between genotype and global DNA methylation is not apparent in primary tumour samples from the same subjects. Moreover, the level of Cpg island hypermethylation in specific tumour suppressor genes is similar for all three MTHFR variants (Paz et al. 2002).

In contrast, in vitro and in vivo studies have consistently found that DNA stability (measured using a variety of biomarkers) is unaffected by genotype. The ability of lymphocyte DNA in vitro to resist uracil misincorporation and chromosomal damage is comparable for all genotypes (Crott et al. 2001a,b). In vivo, endogenous DNA strand breakage, sister chromatid exchange and micronuclei formation in blood cells is similar for all MTHFR C677T variants (Zijno et al. 2003). Moreover, endogenous uracil misincorporation in lymphocyte DNA from healthy control subjects is unaffected by C677T genotype, and is independent of folate status and smoking habit (Narayanan et al. 2004).

Thus, there is little support for the hypothesis that the C677T MTHFR variant reduces the risk of malignancy by increasing the availability of 5,10-methylenetetrahydrofolate for thymidine and purine synthesis, decreasing uracil misincorporation into DNA and thereby increasing genomic stability, which is disappointing. However, necessarily the majority of data has been collected in studies using surrogate tissues such as peripheral blood lymphocytes, and the effect genotype on uracil misincorporation and DNA stability in the human colon remains unknown. Moreover, the influence that other dietary micronutrients such as vitamin B<sub>6</sub> and riboflavin have on MTHFR activity, DNA stability and cancer risk has not been established (McNulty et al. 2002; Moat et al. 2003).

As discussed previously, MTHFR activity (and colorectal cancer risk) is profoundly influenced by folate status. A recent human study investigating the associations between the C677T MTHFR polymorphism, smoking and folate status on colonic dysplasia has reported some startling findings (Ulvik et al. 2001). Folate status and genotype act to modulate the procarcinogenic effect of smoking. In smokers with the T allele (both CT and TT individuals) low folate intake is associated with an increased risk of developing high-risk adenomas. This finding could be explained by the induction of DNA hypomethylation by low folate and reduced enzyme activity (see earlier, p. 574). However, high folate status and smoking in subjects with the homozygous wild-type genotype (CC) also increases the risk of malignancy, presumably by accelerating the growth of already initiated (by smoking) colon epithelial cells (Ulvik et al. 2001). While this complex study could be criticised for lacking statistical power after stratifying subjects according to genotype, folate status and smoking habit, data from animal models also show that folate can act either to reduce malignant transformation or to accelerate carcinogenesis. This differential effect is critically dependent on the time of intervention and the model system employed. Rats treated with the colon carcinogen azoxymethane and made folate deficient have markedly fewer aberrant crypt foci (an early indicator of malignant transformation) in the colon than control animals (Le Leu et al. 2000). Similarly, folate given before establishment of neoplastic foci lowers the number of colonic aberrant crypt foci and adenomas in a mouse model of familial colo-rectal cancer combined with a deletion in mismatch repair (Apc<sup>+/−</sup>− Msh2<sup>−/−</sup> mice; Song et al. 2000). Conversely, when administered after the development of neoplastic lesions in the same model elevated folate acts to increase formation of intestinal adenomas (Song et al. 2000).

Thus, folate may be protective against initiation of carcinogenesis, but may act to accelerate progression of the cancer in pre-existing neoplastic cells.

Is it possible to set an RDA for folate and vitamin B<sub>12</sub> to ensure optimum DNA stability?

Deficiencies in micronutrients that are either required as cofactors for DNA metabolism and repair (like folate and vitamin B<sub>12</sub>) or form an integral part of the DNA molecule (like Zn) may have as destructive an effect on DNA as...
radiation or chemical carcinogens (Ames, 2001). This situation has led to the concept of creating a RDA to ensure optimum genomic stability in man (Ames, 2001; Fenech, 2001b; for review, see Fenech, 2003). Currently, RDA for vitamins and minerals are based on the prevention of acute overt deficiencies. A RDA allowing optimum genomic stability would require redefinition based on the prevention of cancer (Fenech, 2003). It is clear that folate (and vitamin B12) is crucial for normal DNA metabolism and repair and for controlling appropriate gene expression, and that deficiencies in both B vitamins cause genomic instability in vitro and in vivo. Is it possible to determine what level of B vitamins may be optimal for preventing damage to DNA by further examining data from experimental studies? Uracil misincorporation and DNA strand breakage are negatively correlated with folate acid levels, and decrease dose-dependently in cultured human lymphocytes and colonocytes supplemented with increasing concentrations of folic acid (Duthie & Hawdon, 1998; Duthie et al. 2000b). Both biomarkers of DNA damage are minimised after in vitro intervention with 100 μg/folic acid (Duthie & Hawdon, 1998; Duthie et al. 2000b). Similarly, uracil misincorporation and micronuclei frequency are at their lowest in cultured human lymphocytes supplemented with 120 μg/folic acid (Crott et al. 2001a,b). In a placebo-controlled human study intervention with folic acid (700 μg) and vitamin B12 (2·5 μg) for several months has been found to reduce lymphocyte micronuclei frequency by 25% (Fenech et al. 1998). In a recent review of data from human trials Fenech (2003) has proposed that genomic instability can be minimised when plasma folate is >34 nm and vitamin B12 is >700 nm and vitamin B12 is >300 pm. Studies using a decrease in micronuclei frequency as an indicator of enhanced genomic stability indicate that a RDA of 700 μg/d for folic acid and 7 μg/d for vitamin B12 would be sufficient to ‘secure’ genomic stability in young adults (Fenech, 2001b). Increasing folate intake can markedly decrease endogenous uracil misincorporation in lymphocyte DNA from volunteers taking 1·2 mg folic acid/d for 3 months (GB Basten, MH Hill, N Vaughan, SJ Duthie and HJ Powers, unpublished results). It remains to be established whether a lower intake of folate would have a similar beneficial effect.

The earlier data suggest that genomic stability can be improved by increasing intake of folate (and vitamin B12), above the current RDA, and it is likely that this increase can only be achieved through supplementation or food fortification. This method might also have additional benefits in terms of decreased incidence of neural-tube defects, heart disease and ageing-associated degenerative disorders such as cognitive impairment.

Summary

In addition to exogenous and endogenous mutagens and carcinogens, inappropriate nutrition can induce DNA damage and ultimately cancer.

Data from human observational and supplementation studies, animal models and in vitro cell-culture experiments strongly support a role for folate in maintaining genomic stability, acting either through its ability to maintain normal DNA synthesis and repair or through its ability to control gene expression via DNA methylation. Currently, the relative importance of these pathways is unknown.

Risk from cancer appears to be influenced by polymorphisms in key folate-metabolising genes, although the mechanism of cytoprotection remains elusive. However, while it is clear that folate protects against DNA damage and initiation of carcinogenesis, recent data from several animal experiments and one human population study suggest that high folate intakes may be detrimental to individuals with specific genetic polymorphisms who also smoke, by accelerating progression of cancer. This disturbing finding, together with the data from human intervention studies suggesting that the dietary intake of folate required to optimise DNA stability is substantially higher than the current RDA, obviously raises important safety and ethical concerns in the debate over the potential benefits to human health of mandatory fortification of certain foods with folate.

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