Colorectal carcinoma and folate

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About 75% of the patients have sporadic forms of the disease. The remaining 25% of the patients have a family history of the disease, suggesting a contribution for shared genes and environment; however, only 5-6% of CRC is due to mutations at high-penetrance of genes that lead to the development of this malignancy (APC, hMLH1, MUTYH etc.) 3. The major CRC genetic syndromes that increase the CRC risk are: Familial Adenomatous Polyposis (FAP), Attenuated FAP (AFAP), MUTYH-Associated Polyposis (MAP), and Lynch Syndrome (Hereditary Nonpolyposis Colorectal Cancer HNPCC). FAP and Attenuated FAP result from germline mutations in the tumor suppressor Adenomatous Polyposis Coli (APC) gene present on chromosome 5 (5q21) (Table I).

The C-terminal region of the protein is responsible for the co-localization of the protein APC with the microtubules of the cytoskeleton and promotes the assembly of microtubules. APC also controls the intracellular levels of β-catenin, a protein involved in gene transcrip-
tion; the protein Apc regulates the signal transduction through interaction with the $\beta$-catenin, The severity of the disease and the presence of extracolonic manifestations seem to correlate with the location of the mutation inside APC.

**Folate metabolism, methylation and DNA synthesis**

Folic acid or vitamin b9 is composed by the union of three molecules: 6-metilpterina acid, p-aminobenzoic acid (PABA) and glutamic acid. The first two form a molecule of acid pteroico that, as a result of binding to the glutamate, form the pteroilglutammico acid or folic acid (Fig. 1).

**ABSORPTION AND METABOLISM**

The absorption of folate occurs at the level of the small intestine 'via' the RFC1 (reduced folate carrier) that hydrolyzes it to 5-metilTHF, the predominant form in the plasma, but this process becomes saturated at a dose of 250, $\mu$g; so wherein the remaining portion of the ingested dose, 400 $\mu$g, is transported directly into the cell without being hydrolyzed.

Folates are both donors that acceptors of methyl groups, used in the synthesis and methylation of DNA, RNA and proteins. This important biological function is located as a point of convergence of various metabolic processes, whose common denominator is the MTHFR (methyleneetetrahydrofolate), an enzyme that converts in an irreversible way, the 5,10-metileneTHF in 5-metilTHF, involved in the synthesis of purines (adenine, guanine), of deoxythymidine (dTMP) and in the formation of methionine from homocysteine.

The 5,10-metileneTHF is the substrate for thymidylate synthase (TS), which transfers a methyl group to a molecule of desossiuridinamonofosfato (dUMP) to form the deoxythymidine monophosphate (dTMP) and is the only way for its 'de novo' synthesis in mammals.

The 5,10-metileneTHF is also used for the production of formilTHF, used for the 'de novo' synthesis of purines and as a donor of methyl groups in the remethylation of homocysteine to methionine by the enzyme methione synthase (MTR). Methionine is converted to S-adenosylmethionine (SAM), which performs two functions, either as donor of methyl groups in the reactions of DNA methylation both as MTHFR inhibitor. The changes in the distribution of methyl groups for alteration of folate metabolism have an impact on both the DNA methylation and DNA synthesis, being finally crucial in the cellular processes of neoplastic transformation.

Normal colon epithelium deficiency of folate appears to increase the risk of colon cancer, while supplementation with folic acid seems to have the opposite effect; on the other hand once foci of aberrant crypts are established, the deficiency of folate could induces regression of these precancerous lesions.

An interesting study has suggested that fortification with folic acid in the mother's diet (recommended dose for women of reproductive age) protects against the development of CRC in the offspring. The protective effect could be in part mediated by an increase of the global methylation of the DNA and a decrease of DNA damage in the colon rectum.

It has been noticed the repair of oxidative damage in human lymphocytes and colonocytes is delayed in a growth medium deficient in folic acid. The 8-oxo-dG transitions induces G: C to T: A, lesions repaired by hOGG1; O6-methylguanine can cause equally transitions by G: C to A: T and a decrease of the activity of MGMT (enzyme repairing such lesions) is associated with mutations in the K-ras protooncogene. It has been observed that increases the activity of these two enzymes involved in DNA damage repair the liver, but not in the mice colon; therefore a deficiency of folic acid might reflect...
Genomic and epigenomics instability

The two main forms of genomic instability, which have been identified in colon cancer, are the microsatellite instability (MSI or MIN, Microsatellite Instability) and the chromosomal instability (CIN, Chromosomal Instability); a subset of colorectal cancers show epigenomics instability that results in an altered methylation of tumor suppressor genes (CIMP, CpG Island methylator phenotype) 17,18.

The microsatellite instability (MSI) consists in lengthening or foreshortening of a sequence of repeating units of 1-6 base pairs; this represents a characteristic of tumors presenting the inactivation of one of the genes involved in MMR (mismatch repair) such as $\text{MSH2}$, $\text{MLH1}$, $\text{MSH6}$, and $\text{PMS2}$. Almost all cancers CRC with Lynch syndrome (Table I) are MIN and constitute about one-third of CRC MIN; the remaining MIN tumors are sporadic and derived from somatic inactivation of the $\text{hMLH1}$ gene, caused by inactivation of its promoter 19. CIN is the most common type of genomic instability observed in colon cancer and occurs in 80%–85% of colorectal tumors 20. It is also known as non-cancer MIN (or MSS, Microsatellite Stable). It is characterized by chromosomal rearrangements and numerical abnormalities, with aneuploid or polyploid aspect, deletions and allelic loss of heterozygosity (LOH) 21. The most frequent are located in the chromosomes 18q, 17p, and 8p (Table II). Changes in the number of copies have been found in different types of cancer contributing both to the development and progression of the tumor, through the inactivation of suppressor genes and activation of oncogenes 22.

The chromosomal instability is an efficient mechanism for losing the “wild-type copy” of the tumor suppressor gene, as is the case $\text{APC}$, $\text{TP53}$ and $\text{SMAD4}$ 23. MIN tumors have a better prognosis than tumors CIN.

**Table II - Each row lists the most frequent aberrations found in CRC 4.**

<table>
<thead>
<tr>
<th>Chromosome loss</th>
<th>Chromosome gain</th>
</tr>
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<tbody>
<tr>
<td>18, 17p, 1p, 4, 14, 5q, 21</td>
<td>7, 12, X, 5, 8</td>
</tr>
<tr>
<td>18q21</td>
<td>20q13</td>
</tr>
<tr>
<td>18q</td>
<td>20q</td>
</tr>
<tr>
<td>18p12-ter, 15q11-q21, 17p12-13, 18q12-21</td>
<td>8q23-ter, 13p14-31, 20q13</td>
</tr>
<tr>
<td>4, 18p, 14q</td>
<td>17p, 17q, 1q11, 12p, 19</td>
</tr>
<tr>
<td>8p, 18q, 1p22, 4q26, 15q21</td>
<td>20, 8q, 8q28, 16q24.3, 20q13</td>
</tr>
<tr>
<td>18q</td>
<td>13q</td>
</tr>
<tr>
<td>18, 17p, Y, 1p3, 8p</td>
<td>13, 20, 7, X, 12, 6</td>
</tr>
<tr>
<td>8p, 18, 18q</td>
<td>3, 3q, 5, 5p, 7, 8q, 20, 20q, 13, X</td>
</tr>
<tr>
<td>4, 5, 8, 10, 14, 15, 17, 18, 21, 22, Y, 18q10 [i(8)], 17q10 [i (17) (q10)]</td>
<td>7, 13, 20, X</td>
</tr>
<tr>
<td>18q12</td>
<td>7, 13, 20, X</td>
</tr>
</tbody>
</table>

CIMP: The CIMP phenotype is characterized by the presence of hypermethylation of CpG islands in the promoter of many genes. CpG islands are small genomic regions (~ 500bp 1kb) localized at the level of the 5' region of 75% of human genes and are generally unmethylated. However, there is a small subset of highly methylated CpG islands, those ones of genes expressed only in one copy (genes “imprinted”), inactivation genes of the X chromosome in women, tissue-specific genes; additionally various CpG dinucleotides, outside the CpG islands, in particular those ones located within the repeated regions of DNA, are methylated. DNA methylation consists in the addition of a methyl group (CH3) to a cytosine residue and plays a very important role in the regulation of gene expression.

DNA methylation in colorectal CARCINOMA

DNA methylation plays therefore a very important role in the regulation of gene expression; in fact the CH3 group interferes with the binding of transcription factors, but may also acts indirectly by recruiting the methylated DNA binding proteins that in turn call enzymes able to methylate histones and to deacetylate histonic tails: this whole process leads to the configuration of “closed chromatin” and to the “gene silencing”24. The methylation of cytosine is also an important factor mutation, while in fact the deamination of cytosine produces uracil (base immediately recognized as foreign to the DNA), the deamination of 5-methylcytosine transforms it into thymine, generating a mismatch, that the MMR system is not always able to repair. A more extensive methylation of CpG islands has been associated in many studies to the inactivation of the regulatory regions of several genes, such as tumor suppressor genes. Hypomethylation at the level of the promoter of the
proto-oncogenes or hypermethylation of tumor suppressor genes in these regions cause a selective development and transformation of the cells \(^{25}\). The tumor suppressor genes are in fact involved in a wide range of cellular processes including the regulation of cell cycle, DNA repair, apoptosis, angiogenesis, invasion, migration and cell adhesion \(^{26}\).

Wasson and collaborators (2006) observed a global hypomethylation in the presence of cells deprived of folic acid \(^{27}\). Hypomethylation of DNA is a frequent phenomenon in many types of tumors and typically occurs in repeated sequences residing in satellite or pericentric regions; hypomethylation makes the chromosomes more susceptible to breakage and thus leads to chromosomal instability (CIN) or activation of proto-oncogenes such as K-RAS \(^{25}\). A study reported an altered methylation of the gene CDKN2A (p16), i.e. tumor suppressor, in patients with CRC (mainly at the level of the right colon) and with adenomas of the colon-rectum; patients with absence of methylation of p16, as compared to those ones with its hypermethylation, also exhibited an higher survival \(^{28}\).

The loss of expression of UNC5C and DCC (deleted in CRC) has been associated with their methylation \(^{29}\), \(^{30}\); altered methylation of these genes was observed, respectively, in 68% and in 56% of cases of primitive CRC. Hibi and Nakao (2006) analyzed the methylation status of the promoter of p16, p14, hMLH1, CDH13, RUNX3 and CHFR in 58 CRC primitive patients and its correlation with the disease characteristics of the patients; these Authors observed a significant difference between the number of methylated genes and the stage of colon cancer \(^{31}\).

Germline mutations of the APC tumor suppressor gene cause FAP and the same somatic mutations are common in sporadic CRC \(^{32}\). The promoter hypermethylation 1 A of APC has been reported as an early stage of carcinogenesis in many tumors \(^{31}\). A study enrolling 65 cases of CRC, 8 of adenoma, 5 of patients suffering from cancer but presenting normal mucosa and 1 normal case, compared the methylation profile expressed from the pathologic and not pathologic mucosa, demonstrating an altered level of methylation in the promoter of the MGMT gene, hMLH1, p16, MINT1, MINT31, p15, RAR-β \(^{33}\). Table III show examples of genes that undergo epigenetic alterations in CRC.

### Table III - Some epigenetic alterations found in the CRC \(^{4}\).

<table>
<thead>
<tr>
<th>Gene</th>
<th>Function</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>APC</td>
<td>Adenomatosis polyposis coli</td>
<td>Tumour suppressor</td>
</tr>
<tr>
<td>MGMT</td>
<td>O-6-methylguanine-DNA methyltransferase</td>
<td>Involved in repairing DNA damage; silencing by hypermethylation</td>
</tr>
<tr>
<td>hMLH1, hMLH2</td>
<td>MutL homolog 1, 2</td>
<td>DNA repair genes; their silencing, by hypermethylation is</td>
</tr>
<tr>
<td>ADAM23</td>
<td>A disintegrin and metalloprotease domain 23</td>
<td>Members of this family are membrane-anchored proteins and</td>
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<tr>
<td></td>
<td></td>
<td>have been implicated in a variety of biological processes involving</td>
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<tr>
<td></td>
<td></td>
<td>cell-cell and cell-matrix interactions. ADAM23 may be downregulated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>by aberrant promoter hypermethylation during the progression of</td>
</tr>
<tr>
<td>P15</td>
<td>Cyclin-dependent kinase inhibitor 2B</td>
<td>TIS gene is a tumor suppressor, which encodes a cyclin-dependent</td>
</tr>
<tr>
<td>P73</td>
<td>Tumor protein p73</td>
<td>Participates in the apoptotic response to DNA damage. May be a</td>
</tr>
<tr>
<td>CDKN2A/P14</td>
<td>Cyclin-dependent kinase inhibitor 2A, alternated reading frame</td>
<td>Tumour suppressor gene, involved in cell cycle regulation; its</td>
</tr>
</tbody>
</table>

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Environmental risk factors

In the recent years it has been reported that the environment plays a role in epigenetic alterations that are observed in various pathologic conditions, such as cancer of the colon and rectum; in addition to the assumption of folate, there are a number of environmental factors that may contribute to the risk of CRC.

PHYSICAL ACTIVITY AND OBESITY

Numerous epidemiological studies have provided information about the existence of a correlation between physical activity / body mass index and the risk of developing CRC. Overweight people, leading a sedentary lifestyle, are at risk regardless of the type of diet they follow.

Tobacco and Alcohol

Tobacco contains many carcinogens that can bind DNA to form adducts, which can cause irreversible genetic damage to the lining of the colon and rectum. Alcohol intake and smoking habits seem to be involved in the risk of developing colorectal cancer. There is a significant association between colon polyps and consumption of tobacco.

In a study conducted by Ashktorab and co-workers (2007), 48% of cancer cases compared with 5.9% of controls were current smokers, indicating that the chance of having a colon polyp was 15.1 times higher in smokers than in nonsmokers. The smoking predisposes to hypomethylation of numerous genes, with consequent activation of genes, including oncogenes, which contribute to the development of the CRC.

Based on the data available in the literature, which showed that chronic users of alcohol were susceptible to the occurrence of malignancies, Pöschl G. and Seitz H.K. (2004) developed a series of studies to contribute to the understanding how ethanol (made by itself is not carcinogenic) could contribute to the development of tumors. It was observed that acetaldehyde, a metabolite obtained by the oxidation of ethanol by cytochrome P4502E1, is responsible for the carcinogenic effects of alcohol.
The acetaldehyde interferes with the processes responsible for the synthesis and repair of DNA, thus causing the development of tumors, and this was observed in both experiments in-vitro (cell cultures in prokaryotes and eukaryotes) and in-vivo (laboratory animals). One of the enzymes of DNA repair that can be inactivated is O-6 guanine methyl-transferase (MGMT, responsible for the removal of adducts from DNA caused by alkylating agents). When the O-6 methyl-guanine is not “repaired” by MGMT, during DNA replication, it will be erroneously paired with a thymine, giving rise to a point mutation. Another important aspect due to the consumption of alcohol is the DNA methylation. Numerous mechanisms have been hypothesized by which ethanol may interact with folate metabolism and DNA methylation, thus causing cancer. Alcohol affects the absorption, consumption and metabolism of B vitamins (folic acid and pyridoxal-phosphate) involved in the reactions of trans-methylation in the liver, thus decreasing the synthesis of the methyl groups \[\text{H}_2\text{S}\text{COCH}_{3}\]. Additionally, the ethanol reduces the activity of methionine synthase, which (under physiological conditions) adds the methyls to homocysteine forming methionine, using the methyl-thetraidrafolate as a donor of methyl groups \[\text{H}_2\text{S}\text{COCH}_{3}\].

Hamid and colleagues (2009) observed in vivo (in male rats) a decrease in the production of mRNA and of protein expression of RFC1 (Reduced Folate Carrier) after the daily administration of alcohol to guinea pigs. This study suggests that, during the intake of alcohol, there is a decrease in the function of the protein RFC1 and this can then induce the hypomethylation of DNA.

**Fibres**

A high fiber consumption may decrease the likelihood of developing CRC. The mechanism of action by which this effect is obtained has been attributed to the action of dilution of potentially carcinogenic substances within the intestine by the fibers, thereby decreasing the time of contact with the walls. The data in support of this thesis, however, are still controversial.

**Genetic susceptibility to CRC**

Several polymorphisms have been studied as possible risk factors in the development of CRC; polymorphisms in the genes of glutathione S-transferase (GSTs), which produce enzymes involved in the metabolism of potentially carcinogenic substances, have been associated with an increased risk of developing CRC, especially in the Caucasian population.

Various studies report conflicting results concerning the polymorphisms in DNA repair genes and their possible involvement in the risk of CRC. In literature, there are many studies regarding genes involved in the metabolism of folic acid coding for enzymes which have a key role in DNA synthesis and in the processes of methylation; polymorphisms in these genes may be associated with altered methylation of genes involved in development of CRC.

In particular the polymorphisms MTHFR C677T - A1298C, MTR A2756G MTRR A66G, TYMS 28 bp repeats, DNMT 3b (DNA methyltransferase)-149C> T, TCNII (transcobalamin II) variant 776G, often in combination with the intake of folate, have been associated with the risk of CRC, CIMP and MSI.

**Conclusions**

A restricted folate diet and / or polymorphisms in genes that regulate metabolism, either through mechanisms of global hypomethylation of DNA, or through promoter hypermethylation of tumor suppressor genes, appear to be important factors in the promotion and progression of cancer colorectal cancer. However many aspects of this topic are still under investigation, particularly concerning the dose and the time...
of intake of folate, necessary for ensuring a protection. A more large casuistry is necessary, particularly including patients in the preclinical phase and in stage of overt disease, in order to investigate not only the methylation status of the patient suffering from carcinoma of the colon and rectum, but especially that one of the subjects in which the mucosa is still normal or expressing benign adenomatous. This last cohort of patients could benefit of resolutive medical and surgical therapies. To date this is still a woking-progress aimed to understand the controversial role of folates in the development of colorectal cancer.

Acknowledgments

We thank Prof. L. Best for the scientific contribution made to this work.

Riassunto

Più di un milione di individui all’anno in tutto il mondo sviluppa il carcinoma del colon-retto (CRC), con un tasso di mortalità prossimo al 33%. Circa il 75% dei pazienti presenta una forma sporadica del tumore; il rimanente 25% dei pazienti ha una storia familiare del carcinoma del colon-retto. Considerando il 5-6% di CRC dovuto a mutazioni ad alta penetranza di geni che por-

References


