

Mesalazine Improves Replication Fidelity in Cultured Colorectal Cells

Christoph Gasche,¹ Ajay Goel,² Loki Natarajan,³ and C. Richard Boland²

¹Department of Medicine 4, Division of Gastroenterology and Hepatology, Medical University Vienna, Vienna, Austria;

²Baylor University Medical Center, Dallas, Texas; and ³Biostatistics, Cancer Center, University of California, San Diego, California

Abstract

Epidemiologic studies indicate that mesalazine has chemopreventive effects in inflammatory bowel disease-associated colorectal cancer. Most of our general understanding of chemoprevention in colorectal cancer is, however, derived from aspirin, which is structurally similar to mesalazine. Herein we determined the influence of aspirin and mesalazine on replication fidelity in cultured colorectal cells. Flow cytometry was used for quantitation of mutation rates at a (CA)₁₃ microsatellite in HCT116 cells (mismatch repair deficient) and HCT116+chr3 cells (mismatch repair proficient) that had been stably transfected with pIRESHyg2-EGFP/CA13, an enhanced green fluorescence protein-based plasmid, and cultured in the absence or presence of various concentrations of aspirin or mesalazine. Aspirin at doses above 1.25 mmol/L markedly reduced cell growth. Mesalazine doses up to 5.0 mmol/L had no such effect. The mutation rate in mismatch repair-deficient HCT116 cells was $6.8 \times 10^{-4} \pm 9.0 \times 10^{-5}$. In aspirin-treated cultures the mutation rate was $8.2 \times 10^{-4} \pm 1.3 \times 10^{-4}$ (121% of control). Instead, mesalazine lowered the mutation rate in a dose-dependent fashion ($5.5 \times 10^{-4} \pm 1.1 \times 10^{-4}$; 81% of control). The effects of mesalazine were most significant in the M1 fraction ($P < 0.0001$), which represents a mutant population immediate after the polymerase error and were confirmed in mismatch repair-proficient HCT116+chr3 cells. Our data indicate that mesalazine reduces frameshift mutations at a (CA)₁₃ microsatellite in cultured colorectal cells independent of mismatch repair proficiency. This finding suggests that mesalazine improves replication fidelity, an effect that may be active in reducing mutations independent of its anti-inflammatory properties. (Cancer Res 2005; 65(10): 3993-7)

Introduction

Colorectal cancer is a serious complication in patients with ulcerative colitis or Crohn's colitis. Early age at diagnosis, the extent and severity of colonic disease, the presence of primary sclerosing cholangitis, and a family history of cancer represent independent risk factors for the development of colorectal cancer in ulcerative colitis. The discontinuation of 5-aminosalicylic acid (mesalazine, the active compound of sulfasalazine) therapy was also associated with a higher colorectal cancer risk (1), which was in line with previous findings on sulfasalazine (2, 3), a conjugate of 5-aminosalicylic acid and sulfapyridine. Most of our current understanding of chemoprevention in colorectal

cancer is, however, derived from aspirin, acetylsalicylic acid, which is structurally similar to mesalazine. The molecular mechanisms by which aspirin and other nonsteroidal anti-inflammatory drugs exert chemopreventive effects in colon cancer are complex and a matter of ongoing debate. Besides the well-established effects on cyclooxygenase, aspirin and nonsteroidal anti-inflammatory drugs are thought to mediate their antineoplastic properties by other mechanisms including inhibition of nuclear factor κ B (4). Another possible target for the activity of nonsteroidal anti-inflammatory drugs is the improvement of DNA replication. The fidelity of DNA replication is a product of polymerase accuracy, its proofreading activity, and the proficiency of the postreplicational mismatch repair system (5). Inefficiency of one of these processes can be a key to the development of human cancer, best illustrated by the familial cancer syndrome hereditary nonpolyposis colorectal cancer (also called Lynch syndrome). In hereditary nonpolyposis colorectal cancer, loss-of-function mutations of DNA mismatch repair proteins, such as hMLH1 or hMSH2, reduce the activity of postreplicational DNA mismatch repair and strongly elevate the mutation rate, consistent with the mutator phenotype hypothesis as origin of cancer (6). Aspirin increases mismatch repair protein expression and subsequent apoptosis, suggesting that the up-regulation of the mismatch repair system might be another chemopreventive mechanism of aspirin and related nonsteroidal anti-inflammatory drugs (7). We recently developed a flow cytometry-based assay to study replication fidelity. Frameshift mutations were quantified at a (CA)₁₃ microsatellite that shifted an enhanced green fluorescence protein (EGFP) into a +2 position, thereby leading to expression of a truncated nonfluorescent peptide (8, 9). With this assay, we detected three cell populations according to their fluorescence intensity: nonfluorescent, nonmutant M0 cells; dim fluorescent, intermediate mutant M1 cells; and strong fluorescent, definitive mutant M2 cells (9). We showed that intermediate mutant M1 cells actually carry (CA)₁₃-(GT)₁₂ DNA heteroduplexes that are only present immediately after the polymerase error. Failure of mismatch repair resulted in generation of definitive mutant M2 cells that carry (CA)₁₂-(GT)₁₂ DNA homoduplexes. Herein we applied this assay to test a possible effect of aspirin and mesalazine on replication fidelity in cultured colorectal cells.

Materials and Methods

Cell culture. Details of the *in vitro* bioassay to study mutation rates at a (CA)₁₃ repetitive sequence have been previously described (9). In brief, a (CA)₁₃-(GT)₁₃ oligonucleotide was inserted after the translation initiation codon of the *EGFP* gene of the plasmid pIRESHyg2-EGFP resulting in the plasmid pIRESHyg2-EGFP/CA13. In this construct, the downstream portion of the *EGFP* gene had been shifted out of its reading frame, resulting in expression of a truncated missense peptide

Requests for reprints: Christoph Gasche, AKH Wien, KIM4, Währinger Gürtel 18, A-1090 Vienna, Austria. Phone: 43-1-404004764; Fax: 43-1-404004735; E-mail: christoph.gasche@meduniwien.ac.at.

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without fluorescence. Deletion of 2 bp within this dinucleotide repeat shifts the *EGFP* gene into the proper reading frame and causes expression of EGFP. The pIRESHyg2-EGFP/CA13 construct had been stably transfected into HCT116 colorectal cancer cells (ATCC no. CCL-247), which are mismatch repair deficient by homozygous mutation of the *hMLH-1* gene, and HCT116+ch3, which are mismatch repair proficient through transfer of chromosome 3 (10). For all experiments, well-characterized single cell clones from HCT116 cells (clones A1.3 and A2.1) and from HCT116+ch3 cells (clones A3.1, A3.3, and A3.7) were used. Cells were grown in Iscove's modified Dulbecco's medium (Life Technologies Inc., Rockville, MD) as described (9).

Mesalazine (generously provided by Dr. Falk Pharma, Freiburg, Germany) and aspirin (purchased from Sigma Chemical Co., St. Louis, MO) were dissolved in DMSO and sterile filtered. Twenty-four hours after initial cell sorting, mesalazine or aspirin was added to quadruplicate cultures at a final concentration of 0.0 to 5.0 mmol/L. Corresponding concentrations of DMSO were used as control. All experiments were done at least twice per clone.

A flow cytometry-based assay for mutagenesis. One thousand nonfluorescent cells were sorted into 24-well plates on a FACSVantage SE using CloneCyt Plus sorting technology (Becton Dickinson Immunocytometry Systems, San Jose, CA). After an 8-day growth period at 37°C, 5% CO₂, and full humidity, cells were trypsinized, washed in PBS containing 2% fetal bovine serum (FBS), and resuspended in a total volume of 100 µL PBS/2% FBS. Fifty microliters of cell suspension were analyzed on a FACSCalibur with CellQuest acquisition and analysis software (Becton Dickinson) and the cell counts were doubled to quantitate the total cell number per well. The counts of low fluorescent M1 cells (intermediate mutants), and high fluorescent M2 cells (definitive mutants) were expressed as fractions of the total cell number in culture. Mutation rates were calculated as previously described (9, 11).

Statistics. Means and SEs were calculated for continuous variables (e.g., fluorescence intensity). Cochran-Armitage trend tests were used to compare mutant fractions across different doses of aspirin or mesalazine. The mutation rate is defined as the probability of a cell undergoing a mutation in its lifetime, and is expressed per microsatellite per cell per generation. Mutation rates were estimated using two methods: the method of the mean and the maximum likelihood method (11). A single mutation rate for each dose was estimated by taking a weighted linear combination of the dose-specific mutation rates across clones, with weights chosen to be inversely proportional to the individual variances. All estimated quantities are presented with SEs based on quadruplicate cultures for each clone.

Results

Effect of aspirin and mesalazine on cell viability. We chose to test aspirin and mesalazine for their effect on frameshift mutations in human mismatch repair-deficient colorectal cancer cells. Various concentrations of aspirin and mesalazine were analyzed regarding cell growth. At aspirin concentrations above 2.5 mmol/L, cells started to detach from the bottom of the culture plate within 24 hours. This observation was accompanied by a significant reduction of the total cell number for any aspirin concentration above 1.25 mmol/L at the end of the culture period (Fig. 1). Mesalazine treatment up to 5.0 mmol/L displayed no such effect.

Mesalazine reduces the mutation rate in mismatch repair-deficient cells. The effects of aspirin and mesalazine on mutation rates were further analyzed for any nontoxic dose (aspirin ≤ 1.25 mmol/L, mesalazine ≤ 5.0 mmol/L). Mesalazine, but not aspirin, reduced the mutant fraction in culture in both HCT116-A1.3 and HCT116-A2.1 clones (Fig. 2). Cochran-Armitage trend tests revealed significant decreases in mutant fractions as the dose of mesalazine increased, with χ^2 statistics of 141.91 ($P < 0.0001$) and 106.70 ($P < 0.0001$) for clones A1.3 and A2.1, respectively. For

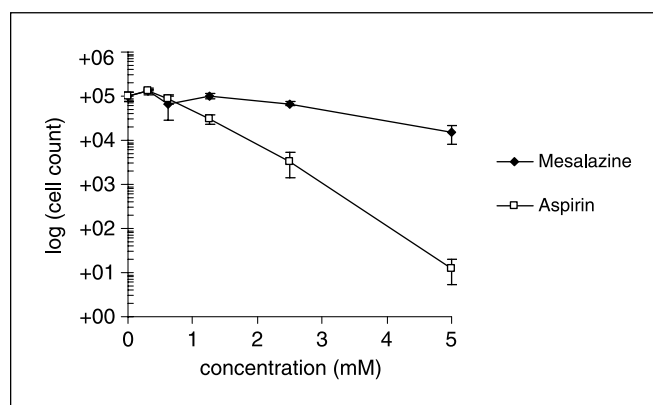


Figure 1. Effect of aspirin and mesalazine on the number of cultured cells. Twenty-four hours after sorting 1,000 cells into 24-well plates, various concentrations of aspirin and mesalazine were added to HCT116-A2.1 cells. Cells were cultured for another 7 days, harvested, and finally the total cell count was analyzed by flow cytometry. A dose-dependent reduction in the total cell count was seen for any aspirin concentrations above 1.25 mmol/L but not for mesalazine up to 5.0 mmol/L.

aspirin the trend test was not significant for either clone (χ^2 statistic = 1.25, $P = 0.26$ for A1.3; χ^2 statistic 1.66, $P = 0.20$ for A2.1). This reduction in mutant cells by mesalazine was mainly caused by a decrease in intermediate mutant M1 cells (Cochran-Armitage test statistics of 159.45 and 103.88 with associated P values of <0.0001 for the clones A1.3 and A2.1, respectively) and also by a reduction in definitive mutant M2 cells (Cochran-Armitage test statistics of 23.59 and 18.71 with associated P values of <0.0001 for the clones A1.3 and A2.1, respectively; Fig. 3). No change in the mutant fraction was observed when cells were cultured in the solvent alone. The combined (across clones) mutation rate dropped from $6.8 \times 10^{-4} \pm 9.0 \times 10^{-5}$ to $5.5 \times 10^{-4} \pm 1.1 \times 10^{-4}$ (81% of control; Table 1). No such change or, rather, an increase was estimated for aspirin ($8.2 \times 10^{-4} \pm 1.3 \times 10^{-4}$; 121% of control; Table 1).

Because the effect was mainly caused by a reduction in M1 cells, we wanted to exclude methodologic errors such as an effect of mesalazine on EGFP fluorescence. HCT116 cells were stably transfected with pIRESHyg2-EGFP, a plasmid that was identical to pIRESHyg2-EGFP/CA13 but lacking the (CA)₁₃ microsatellite, and expressed EGFP within the reading frame. EGFP-expressing cells were cultured with mesalazine and the mean fluorescence intensity was measured by flow cytometry. The mean fluorescence intensity between different cultures ranged from 374 to 448 and was not different between the various mesalazine concentrations and the blank (data not shown). It is therefore unlikely that mesalazine interferes with EGFP fluorescence.

We previously have shown that M2 cells display a deletion of one CA-dinucleotide within the microsatellite (9). The reduction in M2 cells therefore reflects a reduction in the microsatellite mutation rate by mesalazine. Because HCT116 cells are mismatch repair deficient, this effect can only be explained by mechanisms independent of mismatch repair, such as an improvement of replication fidelity. Indeed, mesalazine significantly lowered the number of intermediate mutant M1 cells, which reflects a population of cells immediate after the polymerase error (Fig. 3B). The mutation-protective effect of mesalazine is therefore caused by improvement of polymerase fidelity rather than by mismatch repair fidelity.

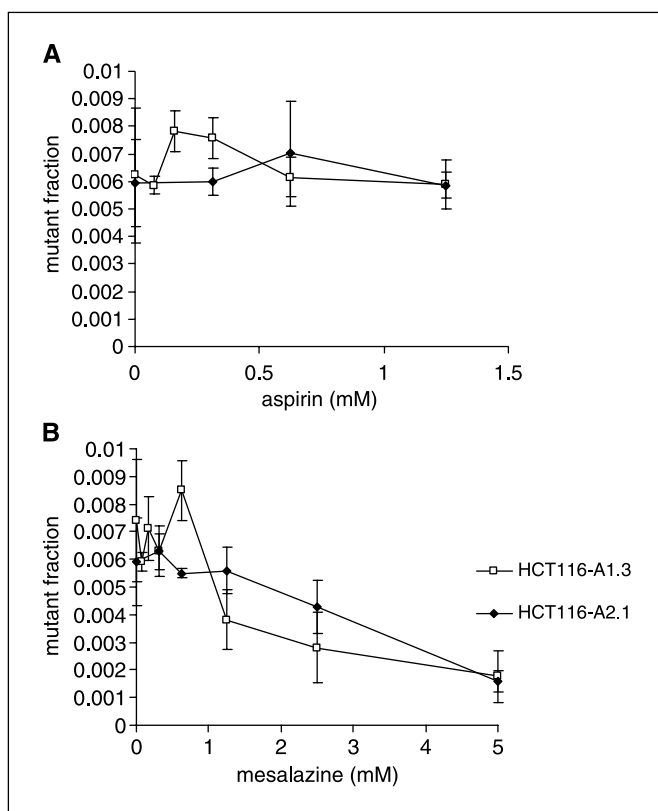


Figure 2. Effects of aspirin and mesalazine on the mutation rate at a $(CA)_{13}$ microsatellite. Nonfluorescent HCT116 cells have been sorted into 24-well plates (1,000 cells/well) and cultured for 8 days with addition of various nontoxic concentrations of aspirin (0–1.25 mmol/L) and mesalazine (0–5.0 mmol/L). Cells were harvested and fluorescent (mutant) cells were quantitated by flow cytometry as described (9). The mutant fraction was calculated as the number of fluorescent cells (M1 and M2) per total cells. Treatment with mesalazine (B), but not with aspirin (A), caused a dose-dependent drop in the mutant cell fraction ($P < 0.0001$ for mesalazine). Points, mean of quadruple cultures for each clone (HCT116-A1.3 and HCT116-A2.1); bars, SE.

Mesalazine improves replication fidelity in mismatch repair-proficient cells. Next, we tested the effect of mesalazine in mismatch repair-proficient HCT116+chr3 clones. As previously observed (9), the intermediate mutant M1 cell fraction in HCT116+chr3 clones ($0.22 \pm 0.05\%$) was somewhat smaller than in HCT116 clones ($0.35 \pm 0.05\%$). HCT116+chr3 cells also did not generate a sizeable number of definitive mutant M2 cells within this short period of time. Therefore, we were unable to measure an effect of mesalazine on generation of M2 cells. Mesalazine decreased the number of M1 cells in a dose-dependent manner (Fig. 3C, $P < 0.0001$). Aspirin or DMSO had no effect on the generation of M1 cells. The effect of mesalazine was also seen when mesalazine was dissolved in ethanol instead of DMSO, showing that the prevention of mutations is an effect of mesalazine and not of the solvent.

Discussion

Herein we present experiments that suggest an effect of mesalazine on the occurrence of frameshift mutations at a $(CA)_{13}$ microsatellite, which is quite different from the chemopreventive effects of aspirin despite the structural similarities. The findings have been generated in a flow cytometry-based

assay using two near isogenic human colorectal cell lines. HCT116 cells originate from a microsatellite instability-positive colorectal cancer from a hereditary nonpolyposis colorectal cancer patient and do not express hMLH1 (12). In HCT116+chr3, the hypermutable phenotype of HCT116 cells has been reversed through transfer of chromosome 3 that encodes a wild-type hMLH1 gene (10). In fact, the mutation rate at the $(CA)_{13}$ microsatellite in HCT116+chr3 cells is 30 times lower than in

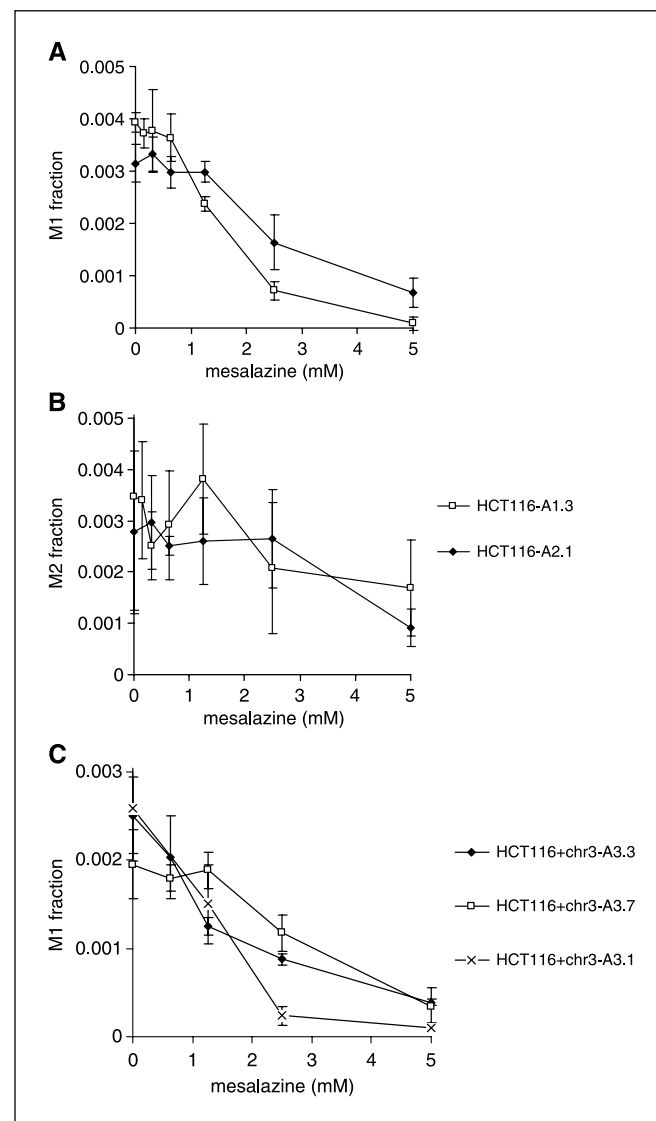


Figure 3. Differential effect of mesalazine on the intermediate mutant (M1) and definitive mutant (M2) population. Subanalyses of the experiments in HCT116 cells testing mesalazine (as described in Fig. 2B) were done. The mutant fraction was separately expressed for M1 cells (A) and M2 cells (B). The effect of mesalazine was greatest for intermediate mutant M1 cells (i.e., early mutation events immediately after the initial replication error; $P < 0.0001$; A). The mesalazine-associated reduction of intermediate mutant M1 cells was followed by a drop in definitive mutant M2 cells at higher mesalazine concentration ($P < 0.0001$; B). A dose-dependent drop in the intermediate mutant M1 cell fraction was also observed in mismatch repair-proficient HCT116+chr3 ($P < 0.0001$; C). A similar drop was seen when mesalazine was dissolved in ethanol (HCT116+chr3-A3.1) instead of DMSO (HCT116+chr3-A3.3 and HCT116+chr3-A3.7). Due to mismatch repair proficiency, HCT116+chr3 cells did not generate a sizeable number of definitive mutant M2 cells. Therefore, the effect of mesalazine on generation of definitive mutant M2 cells was not tested in HCT116+chr3.

Table 1. Mutation rates at a (CA)₁₃ microsatellite for two mismatch repair-deficient HCT116 cell clones estimated by two different computational methods

Treatment	Method of the mean		Maximum likelihood	
	HCT116-A1.3	HCT116-A2.1	HCT116-A1.3	HCT116-A2.1
None	8.9 ± 1.8 (100%)	6.0 ± 1.1 (100%)	7.1 ± 2.1 (100%)	4.8 ± 1.1 (100%)
Mesalazine	6.7 ± 1.8 (75%)	4.9 ± 1.4 (82%)	5.0 ± 2.6 (70%)	4.4 ± 2.1 (92%)
Aspirin	9.6 ± 2.3 (108%)	7.8 ± 1.6 (130%)	7.7 ± 3.0 (108%)	7.4 ± 2.1 (154%)

NOTE: Data $\times 10^{-4}$ are mean \pm SE of mutation rates per microsatellite per generation. Both drugs were used at the highest nontoxic dose (mesalazine at 5 mmol/L and aspirin at 1.25 mmol/L).

HCT116 (9). When transferring our experimental finding from these cell lines into models of human cancer, we would expect that mesalazine could improve replication fidelity and thereby reduce the tempo and frequency of cancer development. Clinical studies have indeed shown that mesalazine and its predecessor sulfasalazine reduce the risk of colorectal cancer in ulcerative colitis (1–3).

Frameshift mutations at microsatellites occur as a time-dependent function of polymerase errors followed by failure of postreplicational mismatch repair. Because the effect of mesalazine was seen in mismatch repair-deficient HCT116 cells and in intermediate mutant M1 cells, mesalazine may act on replication fidelity independent of the postreplicational mismatch repair. Numerous processes determine the fidelity of DNA replication besides mismatch repair. Several of these are responsible for providing undamaged substrates to the replication machinery (e.g., sanitizing deoxynucleotide triphosphate pools, base excision repair, nucleotide excision repair, and single-strand DNA break repair; ref. 13). Next, replication accuracy of undamaged DNA depends on the high nucleotide selectivity and proofreading activity of the various polymerases, which is best illustrated by the emerging relationships between DNA polymerase dysfunction and cancer (14).

Previously we induced frameshift mutations by H₂O₂ in a similar model based on transient transfections (8). In clones from stably transfected cells, however, as used herein, H₂O₂ had no effect on the mutation rate (data not shown). It is likely that this is due to protection of plasmid DNA when integrated into the genome. Because we were unable to induce mutations by H₂O₂, we did not test any protective effect of mesalazine in cultures with H₂O₂.

Currently, we do not understand the molecular mechanism of how mesalazine interferes with the generation of frameshift mutations. We also do not know whether this effect is only true for poly-CA tracts or also for other repetitive sequences. The best known model of frameshift mutations at repetitive sequences involves strand misalignment through template-primer slippage (reviewed in ref. 15). Slippage depends on various factors such as the length of the repetitive sequence, the type of nucleotide (pyrimidine runs show higher slippage rates than purine runs), and the type of polymerase. Frameshift fidelity also decreases when proofreading is suppressed or when the composition of the nucleotide pool is changed (16). Because most control mechanisms of replication affect not only frameshift mutations but also base substitution fidelity, we

may speculate that mesalazine might also prevent missense mutations (5).

The reduction in cell number by aspirin was mainly caused by cell death (17). Mesalazine also reduced cell numbers at the highest concentration tested but rather by growth inhibition. This is in line with previous studies showing accumulation of cells in the S and G₂-M phases of the cell cycle (18). The lower number of mutant cells, however, cannot be explained by simple growth retardation because we measured the mutant cells as fraction of the total cell number at the end of the culture period. However, we cannot exclude that improved replication accuracy takes time and thus may delay cell cycle progression.

The observed effects of mesalazine on replication fidelity were seen at mesalazine concentrations above 1.25 mmol/L (HCT116-A1.3) or 2.5 mmol/L (HCT116-A2.1) and were greatest at the highest dose tested (5.0 mmol/L). Similar or higher mesalazine concentrations were applied in other experimental settings and measured in the colon of patients with ulcerative colitis (19). Mesalazine microgranules reached concentrations above 1 mmol/L in the ileal fluid (20). Because 90% of the oral dose are delivered to the colon, extrapolation of these measurements reveals a colonic mesalazine concentration above 10 mmol/L, which is clearly beyond the highest concentration in our experiments (20).

At the 5.0 mmol/L level, a 19% reduction of the mutation rate was observed in mismatch repair-deficient HCT116. Considering the fact that the tempo of mutations defines the speed of tumor progression (as predicted in the mutator phenotype hypothesis ref. 6), mesalazine therapy could introduce a significantly delay in the clinical manifestation of a tumor. If mesalazine increases the number of years it takes for cells to accumulate the requisite number of mutations required for invasiveness or metastases by 19%, it would significantly reduce the life-threatening manifestations of cancer and diminish cancer deaths even in the absence of reducing cancer incidence. In this respect, mesalazine is potentially useful for prevention of colorectal cancer independent of its anti-inflammatory properties.

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References

1. Eaden J, Abrams K, Ekbom A, Jackson E, Mayberry J. Colorectal cancer prevention in ulcerative colitis: a case-control study. *Aliment Pharmacol Ther* 2000;14:145-53.
2. Pinczowski D, Ekbom A, Baron J, Yuen J, Adami HO. Risk factors for colorectal cancer in patients with ulcerative colitis: a case-control study. *Gastroenterology* 1994;107:117-20.
3. Moody GA, Jayanthi V, Probert CS, Mac KH, Mayberry JF. Long-term therapy with sulphasalazine protects against colorectal cancer in ulcerative colitis: a retrospective study of colorectal cancer risk and compliance with treatment in Leicestershire. *Eur J Gastroenterol Hepatol* 1996;8:1179-83.
4. Kopp E, Ghosh S. Inhibition of NF- κ B by sodium salicylate and aspirin. *Science* 1994;265:956-9.
5. Kunkel TA. Considering the cancer consequences of altered DNA polymerase function. *Cancer Cell* 2003;3:105-10.
6. Loeb LA, Loeb KR, Anderson JP. Multiple mutations and cancer. *Proc Natl Acad Sci U S A* 2003;100:776-81.
7. Goel A, Chang DK, Ricciardiello L, Gasche C, Boland CR. A novel mechanism for aspirin-mediated growth inhibition of human colon cancer cells. *Clin Cancer Res* 2003;9:383-90.
8. Gasche C, Chang CL, Rhee J, Goel A, Boland CR. Oxidative stress increases frameshift mutations in human colorectal cancer cells. *Cancer Res* 2001;61:7444-8.
9. Gasche C, Chang CL, Natarajan L, et al. Identification of frame-shift intermediate mutant cells. *Proc Natl Acad Sci U S A* 2003;100:1914-9.
10. Koi M, Umar A, Chauhan DP, et al. Human chromosome 3 corrects mismatch repair deficiency and microsatellite instability and reduces *N*-methyl-*N'*-nitro-*N*-nitrosoguanidine tolerance in colon tumor cells with homozygous hMLH1 mutation. *Cancer Res* 1994;54:4308-12.
11. Natarajan L, Berry CC, Gasche C. Estimation of spontaneous mutation rates. *Biometrics* 2003;59:555-61.
12. Parsons R, Li GM, Longley MJ, et al. Hypermutability and mismatch repair deficiency in RER+ tumor cells. *Cell* 1993;75:1227-36.
13. Colussi C, Parlanti E, Degan P, et al. The mammalian mismatch repair pathway removes DNA 8-oxodGMP incorporated from the oxidized dNTP pool. *Curr Biol* 2002;12:912-8.
14. Friedberg EC, Wagner R, Radman M. Specialized DNA polymerases, cellular survival, and the genesis of mutations. *Science* 2002;296:1627-30.
15. Kunkel TA, Bebenek K. DNA replication fidelity. *Annu Rev Biochem* 2000;69:497-529.
16. Bebenek K, Roberts JD, Kunkel TA. The effects of dNTP pool imbalances on frameshift fidelity during DNA replication. *J Biol Chem* 1992;267:3589-96.
17. Schwenger P, Bellosta P, Vietor I, Basilico C, Skolnik EY, Vilcek J. Sodium salicylate induces apoptosis via p38 mitogen-activated protein kinase but inhibits tumor necrosis factor-induced c-Jun N-terminal kinase/stress-activated protein kinase activation. *Proc Natl Acad Sci U S A* 1997;94:2869-73.
18. Reinacher-Schick A, Schoeneck A, Graeven U, Schwarte-Waldhoff I, Schmiegel W. Mesalazine causes a mitotic arrest and induces caspase-dependent apoptosis in colon carcinoma cells. *Carcinogenesis* 2003;24:443-51.
19. Staerk LL, Stokholm M, Bukhave K, Rask-Madsen J, Lauritsen K. Disposition of 5-aminosalicylic acid by olsalazine and three mesalazine preparations in patients with ulcerative colitis: comparison of intraluminal colonic concentrations, serum values, and urinary excretion. *Gut* 1990;31:1271-6.
20. Layer PH, Goebell H, Keller J, Dignass A, Klotz U. Delivery and fate of oral mesalamine microgranules within the human small intestine. *Gastroenterology* 1995;108:1427-33.