Cancer Research

Altered Dynamics of Intestinal Cell Maturation in *Apc*$^{1638N/+}$ Mice

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Abstract

Novel imaging of active transcription sites in interphase nuclei of intestinal epithelial cells *in situ* showed that key genes associated with Wnt and Notch signaling were dynamically regulated as the cells underwent normal maturation during their migration along the mouse crypt-villus axis (CVA). However, oscillating patterns of activation of these genes were displaced along this axis in the histologically normal intestinal mucosa of *Apc*$^{1638N/+}$ mice before tumor development. Gene expression profiling then showed that the normal reprogramming of cells along the CVA was dampened in the *Apc*$^{1638N/+}$ mice, with an overrepresentation of c-*myc* target genes among those loci affected in the mutant mice. Moreover, in the *Apc*$^{1638N/+}$ mice, there was a perturbed pattern of expression of lineage-specific markers along the CVA consistent with transcription site repression of the *Math1* gene, and genes encoding enzymes of every step of the tricarboxylic acid cycle were downregulated in the crypt of *Apc*$^{1638N/+}$ mice compared with WT, but not in the villus. These changes may alter energy metabolism and generate a pseudohypoxic state, suggested by elevated expression of Hif1α and its target genes. Thus, although intestinal tumors develop in *Apc*$^{1638N/+}$ mice on focal loss or inactivation of the WT allele, our results show that in the *Apc*$^{1638N/+}$ mouse, inheritance of only a single WT *Apc* allele perturbs the dynamic and complex reprogramming underlying normal cell maturation, which links epithelial function and homeostasis with architectural organization of the intestine. *Cancer Res; 70(13); 5348–57. ©2010 AACR.*

Introduction

Reprogramming of intestinal epithelial cells as they leave the progenitor cell compartment at the base of the crypt and mature along the villi toward the lumen generates the multiple cell lineages necessary for normal functioning of the tissue. Homeostasis is established by the correct allocation of cells to these different lineages. The reprogramming during this cell maturation involves altered expression of genes that drive proliferation and markers of differentiation lineages (1, 2). Disruptions in this reprogramming—either persistent expression of underlying drivers of proliferation or failure of proper differentiation—cause tumor development.

In *Apc*$^{Min/+}$, *Apc*$^{\Delta 716}$, and *Apc*$^{1638N/+}$ mice, intestinal tumors develop when the inherited mutant *Apc* allele is complemented by somatic focal loss, mutation, or silencing of the WT allele (3–7), conforming to the hypothesis that for tumorigenesis, both alleles of a tumor suppressor gene must be inactivated (8, 9). Unclear, however, is how the inherited mutation affects the intestinal mucosa, and the probability of tumor formation, before reduction of *Apc* mutation to homozygosity. For example, an ~85% decrease of APC protein is necessary for the generation of ~1 tumor per mouse (10), but mice that inherit one mutant *Apc* allele, or at tumor risk for other reasons, exhibit an expanded proliferative compartment (11).

We therefore compared the intestinal mucosa of C57Bl6 wild-type (WT) mice to histologically normal mucosa of congenic *Apc*$^{1638N/+}$ littermates, before tumors develop due to focal loss of the WT allele. Unlike *Apc*$^{Min/+}$ or *Apc*$^{\Delta 716}$ mice, in which large numbers of tumors develop within months of birth, only approximately three tumors develop from 6 to 9 months in *Apc*$^{1638N/+}$ mice (6), thus permitting the analysis of effects of the inherited mutant allele before loss of the WT allele and development of mucosal pathology.

A novel method of active transcription site imaging in single cells *in situ* revealed that during normal maturation of intestinal cells along the crypt-villus axis (CVA), regulation of genes associated with Wnt and Notch signaling was much more dynamic than apparent from the analysis of steady-state RNA or protein levels. Moreover, there was significant displacement in the *Apc*$^{1638N/+}$ mice of oscillating patterns of these active transcriptional units responsible for cell reprogramming. These pathways cooperate to maintain crypt cells in a progenitor cell phenotype and in lineage-specific allocation (12). In addition,

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Note: Supplementary data for this article are available at Cancer Research Online (http://cancerres.aacrjournals.org/).

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doi: 10.1158/0008-5472.CAN-09-4593

we also found that the inherited mutation dampened cell reprogramming and perturbed the expression pattern of lineage-specific markers in the villus. Moreover, crypt cells exhibited altered expression of genes that encode enzymes of the tricarboxylic acid (TCA) cycle, and perturbed the expression of Hif1α and its targets. Thus, the single WT *Apc* allele in the $Apc^{1638N/+}$ mouse is insufficient to maintain normal pathways and patterns of cell maturation along the CVA.

Materials and Methods

Mice

Generation, maintenance, genotyping, and pattern of tumor formation of $Apc^{1638N/+}$ mice are described (4, 6, 13). Experiments were approved by the Institutional Animal Care and Use Committee of Montefiore Medical Center and the Albert Einstein College of Medicine. $Apc^{1638N/+}$ mice and $Apc^{+/+}$ littermates were fed a completely defined diet (AIN76A; ref. 13). Upon sacrifice, the intestine was rapidly dissected, portions of each region fixed in formalin and then embedded in paraffin, or were used for isolation of cells from along the CVA.

Transcription site detection

Active transcription sites were detected based on methods described (14, 15). Formalin-fixed, paraffin-embedded sections (4 μm) were heated in a 55°C dry oven for 1 hour, placed in decloaking buffer for deparaffinization, cooled, and treated with ammonia/70% ethanol (20 min) and sodium borohydride (50 min, 4°C) to reduce autofluorescence. Prehybridization with 50% formamide/2XSSC was at room temperature, 30 minutes; slides were hybridized overnight with 20 ng of probe at 37°C, protected from light in a humidified chamber. Probes for fluorescence *in situ* hybridization were designed using the OLIGO-6.0 software, with specificity verified using the National Cancer Institute (NCI) GeneBank BLAST program. For each target nascent transcript, three to eight 50-mer DNA probes were synthesized with four to five modified thymidine bases conjugated to succinimidyl ester fluorescent Cy3 or Cy5 dyes (GE Healthcare). Fluorescence of the multiple probes for each target mRNA localized to a specific site. Following hybridization, slides were washed in prewarmed buffers on a shaker protected from light: 50% formamide/2XSSC, 20 minutes; 2XSSC, 1XSSC, and 0.5XSSC for 15 minutes each; then in PBSM and nuclei stained with 4′,6-diamidino-2-phenylindole (DAPI) before mounting with Prolong gold antifade (Molecular Probes). In transcription site detection, fluorescence intensity of hybridized probes is amplified by the many nascent transcripts within a small volume. Fluorescent signals were detected with an Olympus AX70 microscope, UApo 40X, 1.35NA and PlanApo60X, 1.4NA objectives, and a CoolSNAP-HQ CCD camera (Photometrics) using filters for DAPI (#SP100), FITC (#SP101), Cy3 (#SP-102v2), and Cy5 (#SP104v2; Chroma Technology). Three-dimensional images acquired with a 200-nm Z step size were analyzed using the IPLab software version 3.61 (BD Biosciences). Fluorescent spots were identified as transcription sites on the basis of location within the DAPI-stained nuclei, fluorescence intensity, volume, shape, and absence of autofluorescence detected in the FITC channel. Active transcription sites for each locus were counted in a minimum of 50 well-oriented crypt-villi from three mice per genotype. The percentage of transcription sites for each gene was calculated from the total number of transcription sites and nuclei detected.

Expression array analysis

Epithelial cells were isolated progressively from the top of the villus (F1) to the bottom of the crypt (F10) as described (e.g., refs. 1, 2). Expression profiling with RNA isolated from the F1 and F10 cells for each genotype was done on GeneChip Mouse Genome 430 2.0 Arrays (Affymetrix) for four mice for each cell position and genotype. Mean values by genotype and position for each sequence were calculated; the F1/F10 ratios were calculated for each genotype; and then the absolute value of the ratio of these ratios were calculated.

Western blots

Lysates of cells from fractions F10 (crypt bottom) to F2 (near villus top) were fractionated by electrophoresis, blotted, and specific peptides detected as described (1). Antibodies were as follows: Hif1α (Cayman Chemical), vascular endothelial growth factor (VEGF; Santa Cruz), and Hk2 (Cell Signaling). Cells from fraction 1 (villus tip) were not analyzed due to low yield. The experiment was repeated three times using cells isolated from three different mice of each genotype.

Results

Dynamics of intestinal cell reprogramming in WT and $Apc^{1638N/+}$ mice

Analysis of intestinal cell reprogramming during maturation along the CVA used a validated method that detects active transcription of specific loci in single cells *in situ* (14–18). Because the highest concentration of an RNA sequence is at its site of transcription, fluorescent oligonucleotide probes hybridizing to these transcripts produce a bright image at this site, indicating active transcription of the locus queried (Fig. 1A; additional examples in refs. 14–20). Assay of activation of gene transcription in single cells *in situ*, unlike measurement of steady-state levels of RNA or protein, assesses the state of the "rheostats" (i.e., functional state of the transcriptional machinery) that respond rapidly to internal and external signals. In WT mice, the frequency of cyclin D1 and c-*myc* active transcription sites was higher in cells near the bottom of the crypt (Fig. 1B), consistent with function of these genes in driving cell cycling in this compartment, and with reports that they are direct targets of Wnt signaling, more active at the bottom of the crypt (21–23). Similarly, active Notch1 or Hes1 transcription sites, the latter a direct target of activated Notch signaling, were also more frequent in cells in the lower half of the CVA, although localization was not as striking as for cyclin D1 and c-*myc*. Importantly, reprogramming of cells as they mature along the CVA was highly dynamic: for each gene, there was an oscillating pattern of cells with locus activation along the CVA, which may reflect

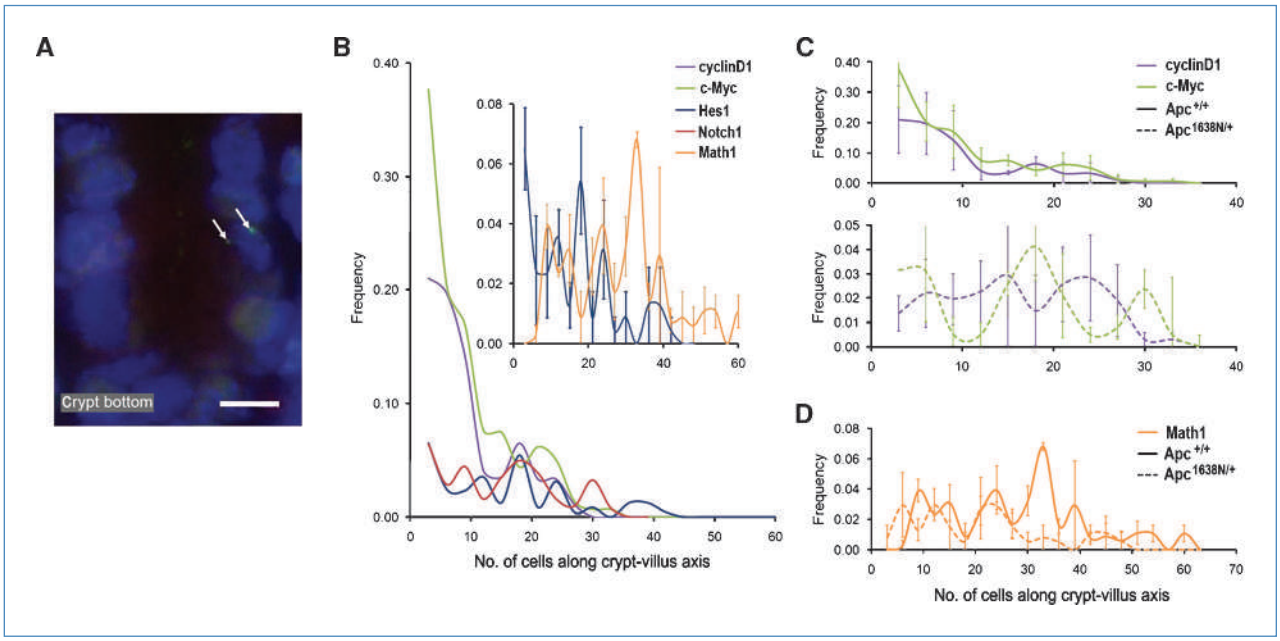

Figure 1. A, two active transcript sites (alleles) encoding Hes1 in an intestinal interphase nucleus. The number of active transcription sites for each gene was scored in relation to cell position from the bottom of well-oriented crypts. Active transcription sites were scored in each of 50 well-oriented crypt/villi, three mice per genotype. Mean number of cells with active transcription sites were binned for each set of three consecutive positions (e.g., 1–3, 4–6) and plotted as a function of position along the CVA. B, frequency of cells with active transcription sites along the CVA for cyclin D1, c-*myc*, Notch1, and Hes1 in WT $Apc^{+/+}$ mice. Inset, direct comparison of positions along the CVA in $Apc^{+/+}$ mice of cells with active transcription sites for Hes1 and Math1. C, top, position of cells with active transcription sites for cyclin D1 and c-*myc* in the histologically normal intestinal mucosa of $Apc^{+/+}$ mice; bottom, of $Apc^{1638N/+}$ mutant mice. D, direct comparison of distribution of cells with active transcription sites for Math1 in $Apc^{+/+}$ and $Apc^{1638N/+}$ mice.

compensatory regulation that overshoots at each position of stimulation and repression, or biological compartmentalization of activation resulting from lateral inhibition during differentiation. These oscillations contrast with monotonic decreases and increases in steady-state expression levels of genes that characterize proliferation or differentiated functions, respectively, along the CVA axis that we reported (1, 2, 24, 25).

Figure 1B (inset) also shows that oscillations of cells with active Hes1 or Math1 transcription sites, both components of Notch signaling, had different periodicities along the CVA, especially at cell positions 18 and 36. Consistent with repression of Math1 by Hes1, there was weak pairwise correlation of *Hes1* and *Math1* active transcription sites (Spearmann coefficient of correlation, r = 0.116, $P = 0.625$), showing that these genes were not transcriptionally active in the same cells at the same time. Indeed, when assayed simultaneously, no cell was identified in which Hes1 and Math1 were simultaneously active, regardless of genotype. In contrast, pairwise correlation of *Notch1* and *c-Myc* was significant (r = 0.618, $P = 0.035$), showing concordant transcriptional activation of these genes that drive proliferation.

The histologically normal mucosa of $Apc^{1638N/+}$ and $Apc^{+/+}$ littermates were compared, with all mice on a congenic C57Bl6 background and fed a chemically defined control diet (AIN76A). This defined, invariant diet minimizes environmental variables (e.g., phytochemical content) that can markedly alter *Apc*-initiated tumorigenesis and thus underlying mechanisms (e.g., refs. 26–29). Differences between the two genotypes were clear: preferential transcription of the *cyclin D1* and c-*myc* genes at the bottom of the crypt of WT mice was shifted to higher positions along the CVA of the $Apc^{1638N/+}$ mice (Fig. 1C). Moreover, a major peak of active transcription of Math1 in the WT mice at cell positions 30 to 36 and a smaller peak at 36 to 42 were absent in the $Apc^{1638N/+}$ mice ($P < 0.002$; Fig. 1D), with additional repression of active Math1 transcription sites at cell position 9 that approached significance ($P = 0.06$).

Attenuated cell maturation in $Apc^{1638N/+}$ mice

Because canonical Wnt and Notch signaling cooperate in regulating intestinal cell maturation, we determined whether alterations in transcription site patterns of $Apc^{1638N/+}$ mice perturbed maturation by assaying expression profiles of villus and crypt cells. We have documented that the cell fractions isolated by sequential elution exhibit gradients of proliferation and differentiation markers that decrease and increase monotonically along the CVA (1, 2, 24, 25). Here, we determined gene expression profiles of the extremes of these gradients: top of the villus (F1 fraction) and bottom of the crypt (F10 fraction) of each of 4 $Apc^{+/+}$ and 4 $Apc^{1638N/+}$ mice.

As expected from different functions of cells in crypts and villi, unsupervised clustering using all 31,213 probe sets unambiguously distinguished cells from these two compartments, regardless of genotype (branch 1 and 2,

Supplementary Fig. S1). These data also suggested genotypes were distinguishable, with three of four mice of each genotype separating between branches 1a and 1b, and 2c and 2d (Supplementary Fig. S1), leading to more in-depth analyses.

Four sets of differentially regulated sequences were distinguished as follows: by crypt or villus position and by genotype (Supplementary Table S1–S4; Supplementary Fig. S2). The 3457 sequences differentially expressed between villus (F1) and crypt (F10) for WT mice were consistent with those we previously reported for intestinal epithelial maturation along the CVA (e.g., enriched in genes contributing to cell cycle regulation, enterocyte differentiation, cytoskeleton assembly, and lipid metabolism; ref. 1). Genotype comparisons identified 73 sequences differentially expressed between the WT and mutant genotypes in the villi (criteria: change >2-fold, and $P < 0.05$) and 259 in crypt cells. Thus, changes were ~4-fold more frequent between genotypes in crypts, in which Wnt signaling is normally active, than in the villi, in which Wnt signaling may be shutdown and therefore not readily compromised.

To address whether the WT *Apc* allele in the Apc^{1638N+} mice was haploinsufficient for regulating normal reprogramming along the CVA, the villus/crypt ratios (F1/F10) for the mean of each sequence were compared. Using combined criteria (>2-fold change, $P < 0.05$), there was no sequence for which F1/F10 was elevated or repressed for either WT or $Apc^{1638N/+}$ mice, but showed reciprocal change in the other genotype (Supplementary Fig. S3), consistent with the apparent normal histology and functioning of the intestinal mucosa in $Apc^{1638N/+}$ mice. However, although there was overlap between sequence subsets for which F1/F10 was altered in WT or mutant mice (Supplementary Fig. S3), there were also distinct differences in extent of change, as illustrated by the following: Sequences were identified differentially expressed between the crypt and villi in the WT mice (F1/F10 >2-fold change, $P < 0.05$), and also altered in the same direction in the mutant mice, but with no criteria imposed for the magnitude of change or *P* value. For the 1,720 sequences downregulated, 82% were downregulated less in the $Apc^{1638N/+}$ mice (Fig. 2A, area under the red dotted line); for the 1,187 sequences upregulated, 68% were upregulated less in $Apc^{1638N/+}$ mice (Fig. 2B). A Z test for binomial proportions showed that the probability that these results were due to chance was very small ($P < 0.0001$). Inserts (Fig. 2A and B) show *P* values for differences in expression in villus(F1)/crypt(F10)

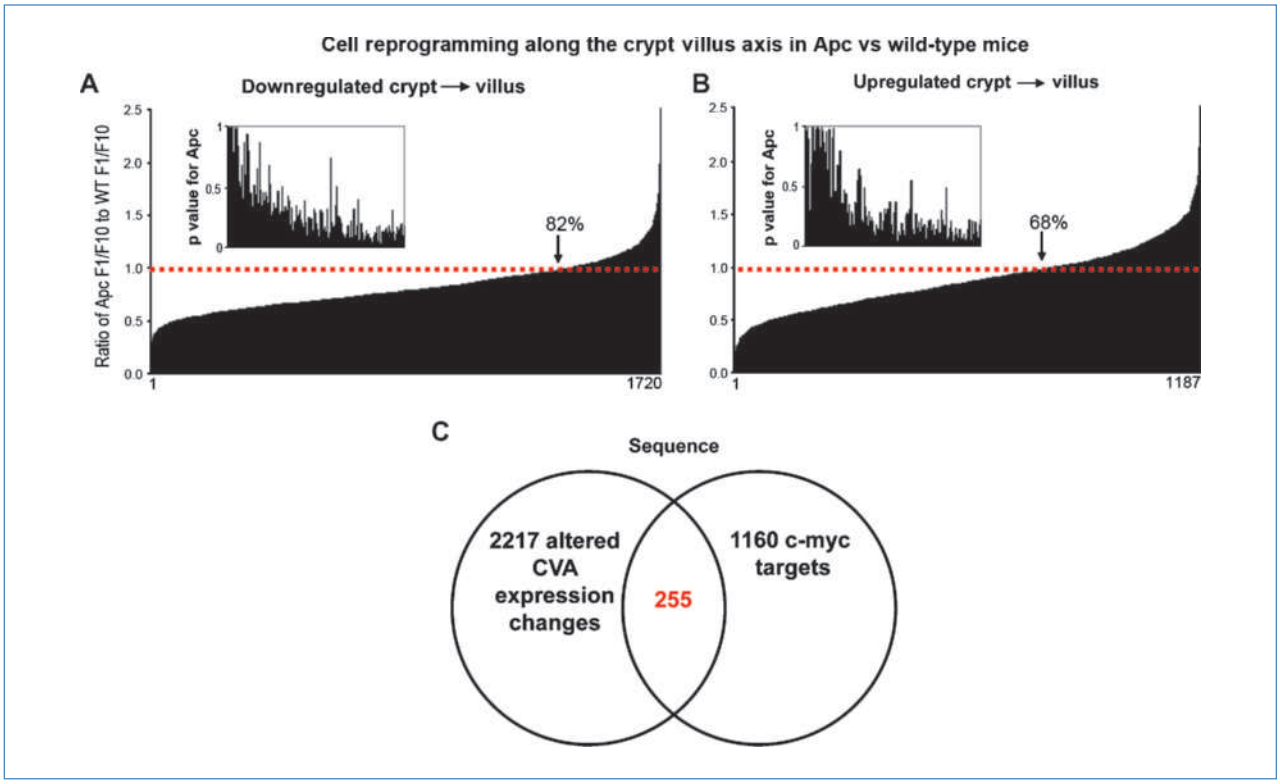

Figure 2. A, 1,720 sequences downregulated in the F1 fraction relative to F10 for both genotypes. B, 1,187 sequences upregulated in F1 fraction relative to F10 for both genotypes. A and B, insets, the *P* values for F1 relative to F10 in $Apc^{1638N/+}$ mice of the same sequences on the ordinates in each panel in the same order. C, overlap between c-*myc* targets and the 2,217 sequences with dampened F1/F10 values (i.e., sequences for which values decrease below the dotted red line in A and B) in the mutant mice compared with F1/F10 in WT. A binomial Z test determined that the intersection of 255 genes was in excess of chance. The underlying probability of selecting a c-*myc* gene was $P = 0.0374$ (= 1,160/31,000); the null hypothesis was $P = 0.0374$ versus $P \neq 0.0374$, and the test was based on randomly selecting 2,217 genes from among the 31,000. The data yielded a z = 19.3, corresponding to $P < 0.0001$; i.e., the 255 genes among the 2,217 identified are in excess of that expected by chance.

for each sequence in the $Apc^{1638N/+}$ mice, with sequences in the same order on the abscissas of both the figures and the inserts. As predicted, sequences that changed less in $Apc^{1638N/+}$ than in WT mice (i.e., those to the left of the *X*-axis; Fig. 2A and B) show higher *P* values in mutant mice and, hence, less significant change. Importantly, for the mutant mice (inserts), most *P* values remain above the significance criteria (i.e., $P < 0.05$); thus, general patterns of cell reprogramming along the CVA in $Apc^{1638N/+}$ mice are maintained, consistent with the normal histology of the tissue, but are dampened compared with reprogramming in the WT mice.

Of the 2,217 sequences attenuated in change along the CVA in mutant compared with WT mice (i.e., below the lines in Fig. 2A and B), 255 overlapped with a c-*myc* target data base of 1,160 sequences (30), a highly significant enrichment of c-*myc* target genes among sequences modulated in alteration in the $Apc^{1638N/+}$ mice ($P < 0.0001$; Fig. 2C). This is consistent with the displaced distribution of c-*myc* active transcription sites in the mutant mice (Fig. 1) and is important in that c-*myc* expression drives normal maturation of intestinal epithelial cells along the CVA (1), and its derepression is necessary for *Apc*-initiated tumor formation (31, 32).

Perturbed lineage-specific markers in $Apc^{1638N/+}$ mice

Wnt and Notch signaling are determinants of lineage-specific allocation of intestinal progenitor cells (33): Math1 expression drives secretory cell differentiation (34, 35), whereas in its absence, the default is enterocyte differentiation (35). We therefore determined whether alterations in transcription site distribution in the mutant mice, and especially repression of Math1 transcription site activation (Fig. 1), was reflected in the expression pattern of lineage-specific markers.

Because sample size was limited and expected differences in expression modest, we present the individual data points for each gene in each of four $Apc^{1638N/+}$ mice compared with four WT mice, along with the median value for each gene, which minimizes the contribution of outliers. Although changes by genotype for each gene were not statistically significant, the overall differences in pattern of expression in the mutant compared with the WT mice were striking (note log scale). The median of 9 of 10 secretory cell markers was lower in the $Apc^{1638N/+}$ mice than in WT (Fig. 3A). This included two markers of the secretion of mucus by goblet cells (Muc2 and Tff3) and seven of eight markers of the heterogenous population of enteroendocrine cells, which secrete a variety of hormones, growth, and neuroendocrine factors. The exception was glucagon, normally a product of pancreatic α cells, but processed by posttranslational cleavage to produce GLP-1 in intestinal enteroendocrine cells. In contrast to this decreased pattern of secretory cell markers, all six enterocyte cell markers were elevated in villus cells of mutant mice compared with WT (Fig. 3A). Thus, although perturbation of expression of each gene is modest in the histologically normal intestinal mucosa of $Apc^{1638N/+}$ mice, the pattern of decreases of secretory and increases in enterocyte markers is consistent with the decrease in active Math1 transcription sites along the CVA.

Deregulated metabolic pathways in $Apc^{1638N/+}$ mice

We reported that dietary risk for colon and intestinal tumors in mice was characterized by decreased expression in the histologically normal intestinal and colonic mucosa of sequences encoding enzymes of the TCA cycle, and suggested that elevated Wnt signaling was associated with shift toward glycolytic metabolism—a metabolic state well documented in colon tumors but not known to exist in the normal tissue

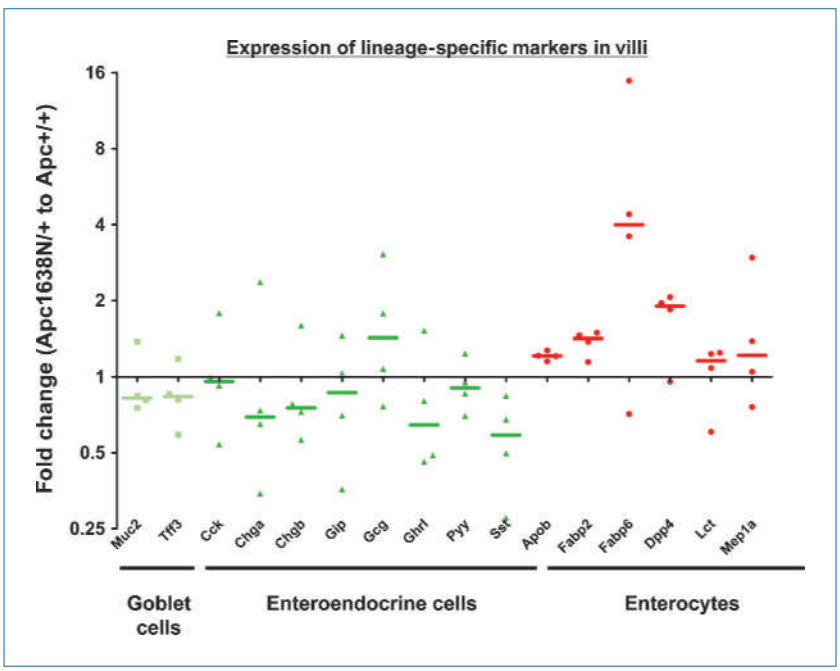

Figure 3. Ratio of lineage-specific marker expression in the villi (F1 cell fraction) of four $Apc^{1638N/+}$ mice relative to four $Apc^{+/+}$ mice. Individual data points and the median for each gene (horizontal line) are shown. Data are plotted on a $\log_2$ *Y* axis for markers of goblet cells, enteroendocrine cells, and enterocytes.

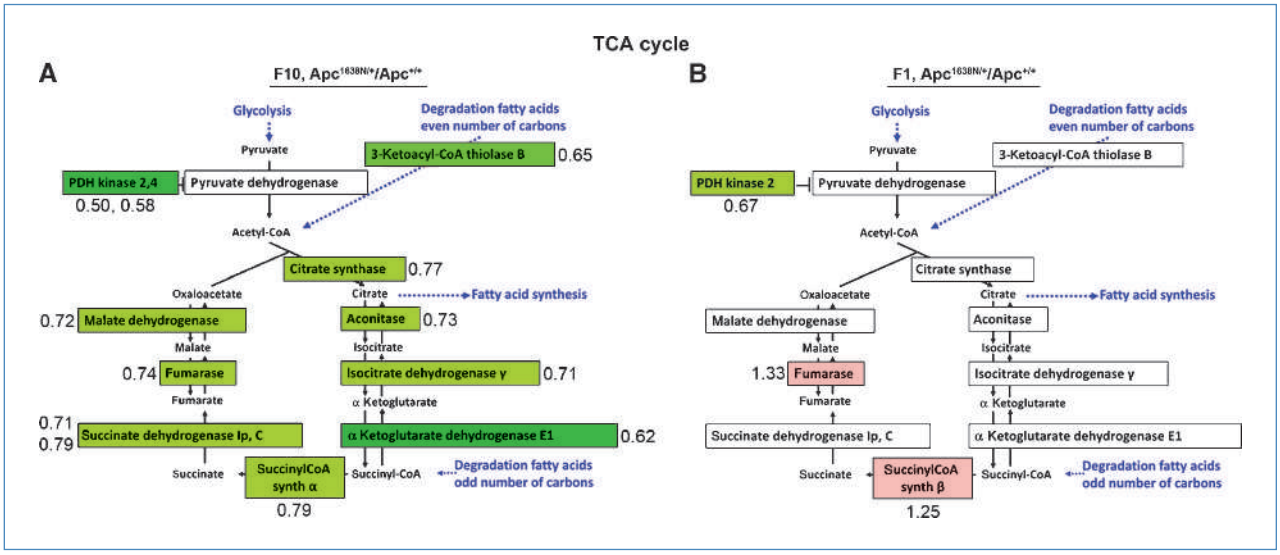

Figure 4. Gene expression profiles were determined using Affymetrix expression arrays (Fig. 2). Ratios of sequence mean expression compared data from F1 cell fractions (top of villus) for four different *Apc*$^{1638N/+}$ mice to the same fraction for four different *Apc*$^{+/+}$ mice. The same was done for F10 cell fractions (crypt bottom). Green, decreased expression; red, increased expression; color intensity, extent of change. For those sequences for which change is indicated, the ratio of expression in *Apc*$^{1638N/+}$ to WT mice is shown next to the sequence. Where there are two numbers, they refer to the two different isoforms of the gene indicated.

at risk (27). We therefore analyzed sequences encoding TCA cycle enzymes in relationship to genetic risk. Expression of the sequence encoding at least one enzyme of every step in the TCA cycle, as well as of 3-ketoacyl-CoA thiolase, which generates acetyl-CoA from metabolism of lipids, was decreased by 20% to 50% in the crypts of *Apc*$^{1638N/+}$ mice compared with WT (Fig. 4A), similar to changes in the mucosa for dietary-induced risk (27). In contrast, these genotype-associated changes were not seen in villus cells (Fig. 4B). Thus, the overall pattern of expression suggests a functional shift in metabolism specifically localized to the bottom of the crypt.

Oncogenic mutations in enzymes of the TCA cycle can generate a pseudohypoxic response and a shift of metabolism toward glycolysis, characterized by increased expression of Hif1α, a transcription factor regulated posttranslationally that coordinates hypoxic response (36, 37). Hif1α protein levels from each of the fractions along the CVA axis of *Apc*$^{1638N/+}$ mice were elevated in a representative experiment (Fig. 5A), and the mean Hif1α protein levels were elevated in each fraction in the mutant mice (three experiments, three different mice of each genotype; Fig. 5B). The elevation increased in fractions 6 to 2 that encompass villus cells expressing differentiated functions (1), although this was not statistically significant for individual cell positions or when the curves were modeled by a repeated measure analysis of patterns of expression across CVA levels and genotypes (Fig. 5). However, VEGF protein, an angiogenic factor regulated by Hif1α, was progressively increased in expression in the same fractions six to two in the villus in *Apc*$^{1638N/+}$ mice relative to WT (Fig. 5A and B). A quadratic model showed this to be a significant genotype by CVA level interaction ($P < 0.015$), suggesting a curvilinear increasing trend from crypt bottom to villus top (Fig. 5). Finally, hexokinase 2, another Hif1α target, was at background levels in every fraction in WT mice but was elevated in every fraction in *Apc*$^{1638N/+}$ mice (Fig. 5A and B). Here, a linear model (Fig. 5) revealed a significant genotype by CVA level interaction ($P < 0.029$), suggesting a decreasing trend from crypt bottom to villus top.

Discussion

These data show that although the intestinal mucosa of the *Apc*$^{1638N/+}$ mouse exhibits normal histology and function, the complex reprogramming of intestinal epithelial cells as they migrate from the progenitor cell compartment in the crypt is perturbed. This was determined by altered patterns of transcriptional activation along the CVA of key genes in the Notch pathway (*Hes1* and *Math1*) and two genes (*cyclin D1* and c-*myc*) that drive proliferation in the progenitor cell compartment regulated by Wnt and Notch signaling, fundamental developmental pathways that cooperate in maintaining the crypt progenitor cell compartment. Expression profiling then showed that although general patterns of reprogramming were maintained in villus compared with crypt cells in the mucosa of *Apc*$^{1638N/+}$ mice, there was a significant compromise in the reprogramming in the mutant mice compared with their WT littermates. These changes in the mutant mice encompassed perturbed profiles of lineage-specific markers and altered expression of sequences that govern metabolic patterns. Changes are modest, consistent with the fact that the tissue continues to appear morphologically and functionally normal, but overall patterns of change indicate that it is significantly perturbed in comparison with the

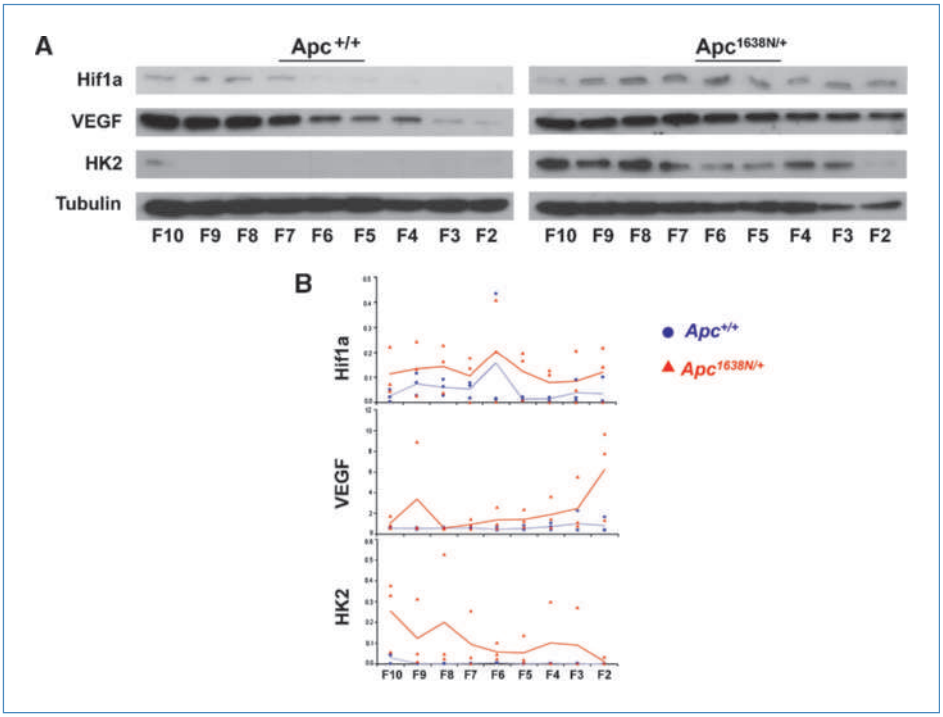

Figure 5. A, immunoblot results from one of the three experiments. B, quantitative analysis of the data from the three different experiments. Mixed models repeated measures analysis was used as an exploratory tool to discover patterns of expression across crypt levels and between genotypes. The models were constructed first with crypt level as a dummy variable and, in cases where there seemed to be a linear or curvilinear trend, as a linear or a quadratic model, respectively. The interaction terms for genotype x crypt level were included in an appropriate way in each of the models, using $P < 0.05$ as a guide to whether a particular model was significant. For Hif1α protein, the data suggest that pattern of expression across crypts-villi is the same for both genotypes but that expression levels for Hif1α are uniformly higher for *Apc*$^{1638N/+}$ mice (although the mixed models repeated measures analysis could not verify this observation). For VEGF protein, the quadratic model revealed significant genotype x CVA interaction ($P_{quadratic} < 0.015$, $P_{linear} < 0.006$), suggesting curvilinear increasing trend in expression from F10 to F2 for *Apc*$^{1638N/+}$ mice, whereas the expression level is relatively constant across crypt-villi for *Apc*$^{+/+}$ mice. For Hk2 protein, the linear model revealed a significant genotype x CVA interaction ($P < 0.029$), suggesting a linear decreasing trend in expression from F10 to F2 for *Apc*$^{1638N/+}$ mice, whereas expression level is relatively constant across crypts-villi for genotype *Apc*$^{+/+}$.

mucosa in WT mice. It has been reported that enterocyte migration along the CVA is decreased in *Apc*$^{Min+}$ mice (38), consistent with the dampened maturation of cells in the villi. Although this was not detected in the *Apc*$^{1638N/+}$ mouse (39), this may be related to the much more modest tumor phenotype in *Apc*$^{1638N/+}$ compared with *Apc*$^{Min/+}$.

In the *Apc*$^{1638N/+}$ *mouse*, loss of the mutant allele is not detected until the development of frank tumors (40), an observation we confirmed (data not shown; ref. 41). Moreover, we determined that the expression of the WT *Apc* allele is reduced in the histologically normal mucosa by 40% to 60%, coupled with a 25% reduction in APC protein of 25% (data not shown). In addition, the *Apc*$^{1638N/+}$ mice do not accumulate significant levels of a truncated APC protein encoded by the mutant allele. Therefore, we conclude that the changes in the underlying molecular biology of the mucosa are due to haploinsufficiency of the WT allele.

The shift of cells exhibiting active *cyclinD1* and c-*myc* transcription, and Notch signaling, along the CVA in the mucosa is important because these genes and pathways likely drive the expanded proliferative compartment that characterizes the mucosa at genetic and/or nutritional risk for tumor development (11). Continued proliferation of cells with a progenitor cell phenotype into zones where cell cycling is normally repressed can contribute to hyperplastic growth and expand the stem-like cell compartment, which must be targeted by the loss of the second *Apc* allele for tumors to form (42). Effects on apoptosis may be less important: rates in the intestinal mucosa are very low and a mutation affecting short-chain fatty acid metabolism that reduce this >90% does not cause tumor development (43). Further, targeted inactivation of Tcf4 in the mouse, which, in complex with β-catenin, is a major effector of intestinal Wnt signaling regulated by *Apc*, leads to postpartum lethality as the mucosa deteriorates and cannot be regenerated due to premature differentiation, but not apoptosis, of intestinal progenitor cells (44).

Math1 drives secretory cell differentiation of intestinal epithelial cells, and in its absence, there is default to the enterocyte lineage (35). Thus, the decrease in 9 of 10 secretory cell markers and the complementary increase in 6 of 6 enterocyte markers were consistent with that predicted by the repression of Math1 transcription sites in the mutant mice. However, altered expression of these markers likely reflects perturbed coordination of differentiation programs, rather than significant shifts in overall lineage allocation, because

the mucosa appears normal until focal loss of the second *Apc* allele and tumor initiation.

A novel finding was decreased expression of genes that encode enzymes of every step of the TCA cycle in crypt cells in $Apc^{1638N/+}$ mice compared with $Apc^{+/+}$ mice, in contrast to the lack of such changes in the villus cells of the same mice. This is similar to alterations we reported in the mucosa of both the small and large intestine of mice at nutritional risk for tumor formation (27), which we recently found is also enriched in the crypt (data not shown). Here, we have shown association of these changes with perturbed expression of Hif1α and its targets VEGF and hexokinase 2. We hypothesize that these data reflect a shift in the tissue toward glycolytic metabolism and generation of a (pseudo)hypoxic state that promotes tumorigenesis. It has been suggested that a shift toward glycolysis favors proliferation, higher in the crypt, by providing biochemical intermediates for synthesis of macromolecules and increase in biomass (45). In regard to the potentially greater shift in the crypts of mutant compared with WT mice, it is important that hypoxia and Hif1α expression are characteristics of stem cell niches (46–50), and that genes encoding enzymes of the TCA cycle are *bona fide* proto-oncogenes that, when mutated, lead to the accumulation of TCA cycle intermediates (51–53) that can trigger Hif1α expression either by succinate inhibition of prolyl hydroxylase activity and/or by generating increases in reactive oxygen species (54). Moreover, elevated Hif1α expression is a direct cause of intestinal polyp formation in Peutz-Jaeghers syndrome, mediating a metabolic shift that drives tumorigenesis (55). Downregulation of the TCA cycle, a shift toward glycolytic metabolism, and a hypoxic response contributing to higher probability of tumor development in the intestinal mucosa by either genetic or environmental influences can be important in both screening strategies for early detection and as targets for chemoprevention.

Wnt signaling may contribute to intestinal tumorigenesis as a continuum of effects related to extent of altered signaling (56), increases in Wnt signaling beyond those sufficient for initiation are necessary for intestinal tumor progression (57), and embryonic stem cell differentiation is modulated as a function of extent of β-catenin signaling levels (58). Thus, it is tempting to speculate that the inherited Apc^{1638} mutation causes modest changes in Wnt signaling that drives the altered transcriptional and expression patterns. Although steady-state levels of expression of several Wnt target genes (c-*myc, cyclin D1, Sox9, Lgr5*, and *jagged1*) were, as expected, higher at the bottom of the crypt of both normal and mutant mice, these steady-state levels were not significantly different at any position along the CVA of $Apc^{1638N/+}$ compared with WT mice (data not shown). However, whether Wnt signaling is functionally altered in the mucosa of $Apc^{1638N/+}$ mice is not easily resolved. For example, if inactivation of one *Apc* allele decreases *Apc* expression, modestly increasing Wnt activity, this would greatly increase the probability that stochastic variations in expression of the WT allele could transiently exceed a threshold sufficient to significantly alter steady-state levels of direct Wnt targets (59). This also applies to the variation in VEGF and Hk2 levels that are seen (Fig. 5), although these changes in $Apc^{1638N/+}$ compared with $Apc^{+/+}$ mice reach statistical significance. Although such focal and transient changes might not be detected in cell populations isolated from the mucosa, the important effect of these stochastic variations in tumor suppressor gene expression has been discussed in detail (59). Alternatively, the alterations in the mucosa of $Apc^{1638N/+}$ mice may depend on perturbation of one of the many other functions that have been reported for APC, rather than changes in Wnt signaling.

In summary, in $Apc^{1638N/+}$ mice, few tumors develop over an extended period and the histologically normal intestinal mucosa can be readily investigated. We have found that in this histologically normal mucosa, there are significant alterations in the dynamics of cell reprogramming along the CVA and of markers of normal cell maturation. We have previously shown that some of these changes are present in the mucosa at dietary risk (27). Thus, just as alterations at distant tissue sites contribute to tumor metastasis by generating receptive environments, probability of tumor development at the primary site may be modulated by alterations that precede the reduction of the inherited mutation to homozygosity, or the generation of initiating mutations. Therefore, these findings have important implications for understanding the mechanism of risk and tumor formation in this tissue, and for clinical approaches to early detection and prevention.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Grant Support

Grants U54CA100926, RO1CA114265, RO1CA135561, R33CA-083208, EB2060, GM80247, and Cancer Center Support Grant P013330 from the NCI.

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Received 12/17/2009; revised 05/03/2010; accepted 05/04/2010; published OnlineFirst 06/22/2010.

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