Cancer Research

Locoregional Effects of Microbiota in a Preclinical Model of Colon Carcinogenesis

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Abstract

Inflammation and microbiota are critical components of intestinal tumorigenesis. To dissect how the microbiota contributes to tumor distribution, we generated germ-free (GF) $Apc^{Min/+}$and $Apc^{Min/+}$;$Il10^{-/-}$ mice and exposed them to specific-pathogen-free (SPF) or colorectal cancer-associated bacteria. We found that colon tumorigenesis significantly correlated with inflammation in SPF-housed $Apc^{Min/+}$;$Il10^{-/-}$, but not in $Apc^{Min/+}$mice. In contrast, small intestinal neoplasia development significantly correlated with age in both $Apc^{Min/+}$;$Il10^{-/-}$ and $Apc^{Min/+}$ mice. GF $Apc^{Min/+}$;$Il10^{-/-}$ mice conventionalized by an SPF microbiota had significantly more colon tumors compared with GF mice. Gnotobiotic studies revealed that while *Fusobacterium nucleatum* clinical isolates with FadA and Fap2 adhesins failed to induce inflammation and tumorigenesis, *pks*$^+$*Escherichia coli* promoted tumorigenesis in the $Apc^{Min/+}$;$Il10^{-/-}$ model in a colibactin-dependent manner, suggesting colibactin is a driver of carcinogenesis. Our results suggest a distinct etiology of cancers in different locations of the gut, where colon cancer is primarily driven by inflammation and the microbiome, while age is a driving force for small intestine cancer. *Cancer Res; 77(10); 2620–32. ©2017 AACR.*

Introduction

Colorectal cancer, the third most common type of malignancy and the third leading cause of cancer-related deaths in the United States (1), involves both genetic and environmental factors. Among the genomic changes associated with colorectal cancers, loss-of-function mutations in the *Apc* (*adenomatous polyposis coli*) gene, a regulator of the WNT signaling pathway, are the most prevalent and are considered the initiating event in approximately 80% of colorectal cancers (2). Of the environmental factors, the gut microbiota is increasingly appreciated as a key player in colorectal cancer pathogenesis. Colorectal cancer patients often carry a distinct microbiota from the healthy population (3). Microbes can modulate colorectal cancer development directly by generating genotoxins, or indirectly and more commonly by mediating inflammatory and immune responses (4, 5). Inflammation is not only a hallmark of colorectal cancer (5), but also an established risk factor for colorectal cancer as supported by epidemiological data from individuals with inflammatory bowel diseases (6).

While human studies provide valuable correlation data on colorectal cancer, much of the mechanistic insight into the disease etiology is obtained from mouse models. Mouse colorectal cancer models can be categorized into two classes: spontaneous and chemical induced (7). Spontaneous colorectal cancer mice carry mutations in genes frequently mutated in human colorectal cancers. The multiple intestinal neoplasia (Min) mouse (referred to as $Apc^{Min/+}$ hereafter), a commonly used animal model of intestinal carcinogenesis, carries a point mutation in one allele of the *Apc* gene and is susceptible to spontaneous intestinal adenoma formation, although predominantly in the small bowel, without exhibiting chronic intestinal inflammation (8). A general protumorigenic role for the microbiota was demonstrated in the $Apc^{Min/+}$ model, as the mice display reduced tumor load in the small and/or large intestine when derived under germ-free (GF) conditions (9, 10). Noticeably, inflammation also enhances development of colon cancer in this model, as seen with the use of dextran sulfate sodium (DSS; ref. 11), by specifically deleting the *Apc* gene in epithelial cells (12), and by genetically introducing defective IL10 signaling (13–15). Inflammation and colonic polyposis in mice with *Apc* deficiency and T cell–specific deletion of *Il10*, $Apc^{\Delta 468}$;$CD4^{Cre}Il10^{f/f}$ mice can be attenuated by antibiotic treatment (14), suggesting that microbiota-driven inflammation underlies colitis-associated colorectal cancer.

The mechanisms by which microbes have been shown to promote development of colorectal cancer are diverse and somewhat specific to each microorganism. For example, enterotoxigenic *Bacteroides fragilis* promotes colorectal cancer through induction of the Th17 response (16), polyketide synthase (*pks*)+ island carrying *E. coli* via production of the genotoxin colibactin

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

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(17), and *Fusobacterium nucleatum* adhesins that either bind E-cadherin to promote tumor growth (FadA) or promote immune invasion and localization to tumors (Fap2; refs. 18–20). Although genetics, inflammation, and microbes play a role in promoting intestinal carcinogenesis in preclinical models, it is unclear how these factors interact and how much each contributes to promotion of colorectal cancer.

To stringently evaluate the relationship between genetic susceptibility to inflammation, microbial status, and cancer, we utilized specific-pathogen-free (SPF) and gnotobiotic *Apc*$^{Min/+}$and *Apc*$^{Min/+}$;*Il10*$^{-/-}$ mice. In this study, we found that inflammation and the microbiota is essential for colorectal but not small intestinal neoplasia in SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ mice. We also demonstrated that colorectal cancer-associated bacteria have differential abilities to promote colorectal cancer with colibactin-producing *E. coli*, but not *F. nucleatum*, inducing colon tumors in *Apc*$^{Min/+}$;*Il10*$^{-/-}$ mice.

Materials and Methods

Animals

The University of Florida Institutional Animal Care and Use Committee approved all animal experiments (Protocol #201308038). 129/SvEv *Apc*$^{Min/+}$ mice were derived GF and crossed to GF 129/SVEv *Il10*$^{-/-}$ mice to generate GF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ mice. GF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ and *Apc*$^{Min/+}$ mice were transferred to the SPF breeding suite and bred for 2 to 3 generations. SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ and *Apc*$^{Min/+}$ mice were either transferred to an SPF housing suite after weaning or remained in the breeding suite, mice transferred to the SPF housing suite were sacrificed at 12, 16, and 20 weeks of age. SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ and *Apc*$^{Min/+}$ mice older than 20 weeks were retired breeders from the SPF breeding suite.

Bacterial strains and culture conditions

F. nucleatum strains were provided by Dr. Emma Allen-Vercoe (University of Guelph), including the inflammatory bowel disease clinical isolate EAVG_016, and colorectal cancer isolates CC53, CC7/3JVN3C1, CC7/5JVN1A4, CC2/3Fmu1, CC2/3FmuA, and CC7/4Fmu3 (used for the 20-week colonization experiment in *Apc*$^{Min/+}$ mice). *E. coli* NC101 or NC101 Δ*clbP* were cultured from glycerol stocks in LB broth, then diluted 1:10 in fresh LB medium and cultured at 37°C before harvesting for gavage. *F. nucleatum* strains were cultured in Brain Heart Infusion Broth (BHI; AS-872, Anaerobe Systems) statically at 37°C in an anaerobic chamber (type B Vinyl, Coy Laboratory). Enumeration of *F. nucleatum* was done by anaerobically plating serial dilutions of culture or fecal materials on fastidious anaerobic agar supplemented with 5% sheep blood.

PCR detection of *F. nucleatum* adhesins

All *F. nucleatum* strains were screened for the FadA and Fap2 adhesins by PCR using the following primers: Fn 16S_F GGATTTATTGGGCGTAAAGC; Fn 16S_R, GGCATTCCTACAAATATCTACGAA; fadA_F CAAATCAAGAAGAAGCAAGATTCAAT; fadA_R, GCTTGAAGTCTTTGAGCTCT (18); fap2_F, AGCCTCTGAGGGTACAAGGT; fap2_R, TGAGCCCCTCCTTCTTCTGA. The screening revealed 4 *F. nucleatum* colorectal cancer isolate strains were *fadA*$^{+}$, *fap2*$^{-}$, and 2 were *fadA*$^{+}$, *fap2*$^{+}$ (Supplementary Fig. S1).

E. coli NC101 *clbP* mutation

Inactivation of gene *clbP* was performed by using the lambda Red recombinase method (21) using primers clbP-P1 (TTCCGCTATGTGCGCTTTGGCGCAAGAACATGAGCCTATCGGGGCGCAAgtgtaggctggagctgcttc) and clbP-P2 (GTATACCCGGTGCGACATAGAGCATGGCGGCCACGAGCCCAGGAACCGCCcatatgaatatcctccttag). The allelic exchange was confirmed by PCR using primers IHAPJPN29 and IHAPJPN30 (22).

SPF microbiota preparation

Cecal and fecal contents were collected from wild-type 129/SvEv mice that were housed under SPF conditions in the animal facility at the University of Florida. One gram of the contents was suspended in 10 mL sterile PBS, broken down using pipette tips, and vortexed. After settling for 2 minutes, the supernatant was transferred to a new tube, mixed with equal volume of sterile 20% glycerol, and frozen at −80°C.

Mouse colonization

Seven- to 12-week GF *Apc*$^{Min/+}$ and *Apc*$^{Min/+}$;*Il10*$^{-/-}$ were transferred to SPF conditions or gnotobiotic isolators as described above. SPF stock microbiota was diluted 1:10^{6} and 200 μL of this mixture was gavaged to each mouse. *E. coli* NC101 or NC101 Δ*clbP* was gavaged at 10^{8} CFU/mouse. For AOM/*Il10*$^{-/-}$ experiments, mice received 6 weekly intraperitoneal AOM (A5486, Sigma) injections (10 mg/kg) starting 1 week post monoassociation with *E. coli* and mice were sacrificed 20 weeks post monoassociation. *F. nucleatum* was gavaged at 10^{8} CFU/mouse when a single strain was used, or 10^{8} CFU per strain per mouse when a mixture of strains were used. BHI medium weekly gavaged mice were used as control for *F. nucleatum* experiments.

Mice were euthanized at indicated time points. The small intestine, cecum, and colon were cut open longitudinally and macroscopic tumors were counted. About 1 × 0.5 cm snips were taken from the proximal and distal colon, flash frozen in liquid nitrogen, and stored at −80°C until analysis. The rest of the colon was Swiss rolled and fixed in 10% neutral buffered formalin solution. Swiss rolls were processed, paraffin-embedded, sectioned and hematoxylin and eosin stained by the Molecular Pathology Core at the University of Florida. Histological scoring of inflammation was performed blindly as described previously (17) and calculated as the average between the proximal and distal colon region scores.

IHC

IHC was performed as described previously (17). Briefly, Swiss roll sections were deparaffinized, rehydrated, and boiled in 10 mmol/L citrate buffer for antigen retrieval. For CTNBB1, the mouse anti-CTNNB1 antibody (1:300 overnight; 6101503, BD Transduction Laboratories) and mouse on mouse (M.O.M.) peroxidase kit (PK-2200, Vector Labs) were used. For PCNA, sections were blocked with 1% BSA, incubated with anti-PCNA clone PC10 (M087901-2, Dako) mouse monoclonal antibody (1:300, 30 minutes), followed by 1:1,000 goat anti-mouse biotin secondary antibody (31800 Fisher), and then incubated with streptavidin–horseradish peroxidase (18–152, Millipore). Liquid DAB^{+} (K3467, Dako) was used according to the manufacturer's instructions for development.

Fecal DNA extraction and 16S qPCR

DNA was extracted using phenol:chloroform separation followed by the DNeasy Blood and Tissue Kit (69506, Qiagen). qPCR

was performed on the CFX384 Touch Real-Time PCR Detection System (1855485, Bio-Rad) using the SsoAdvanced Universal SYBR Green Supermix (1725274, Bio-Rad). The following primers were used: Fuso_F GGATTTATTGGGCGTAAAGC, Fuso_R GGCATTCCTACAAATATCTACGAA; and Eubacteria_F GGTGAATACGTTCCCGG, Eubacteria_R TACGGCTACCTTGTTACGACTT.

16S rRNA sequencing

The V1–V3 region hypervariable region of the 16S rRNA gene was amplified using primer pair 27F (5′-AGAGTTTGATCCTGGCTCAG-3′) and 534R (5′-ATTACCGCGGCTGCTGG-3′). Both the forward and the reverse primers contained universal Illumina paired-end adapter sequences, as well as unique individual 4 to 6 nucleotide barcodes between PCR primer sequence and the Illumina adapter sequence to allow multiplex sequencing (Supplementary Table S1). PCR products were visualized on an agarose gel, before samples were purified using the Agencourt AMPure XP kit (A63881, Beckman Coulter) and quantified by qPCR with the KAPA Library Quantification Kit (KK4824, KAPA Biosystems). Equimolar amount of samples was then pooled and sequenced with an Illumina MiSeq. See Supplementary Data for description of 16S rRNA sequencing analysis.

qPCR examination of inflammatory cytokines

RNA was extracted from frozen tissue snips using TRIzol reagent followed by phenol:chloroform separation. After DNA removal using the Turbo DNA-free Kit (AM1907, Ambion), 10 to 1,000 ng of RNA was used for cDNA synthesis using the iScript cDNA Synthesis Kit (1708891, Bio-Rad).

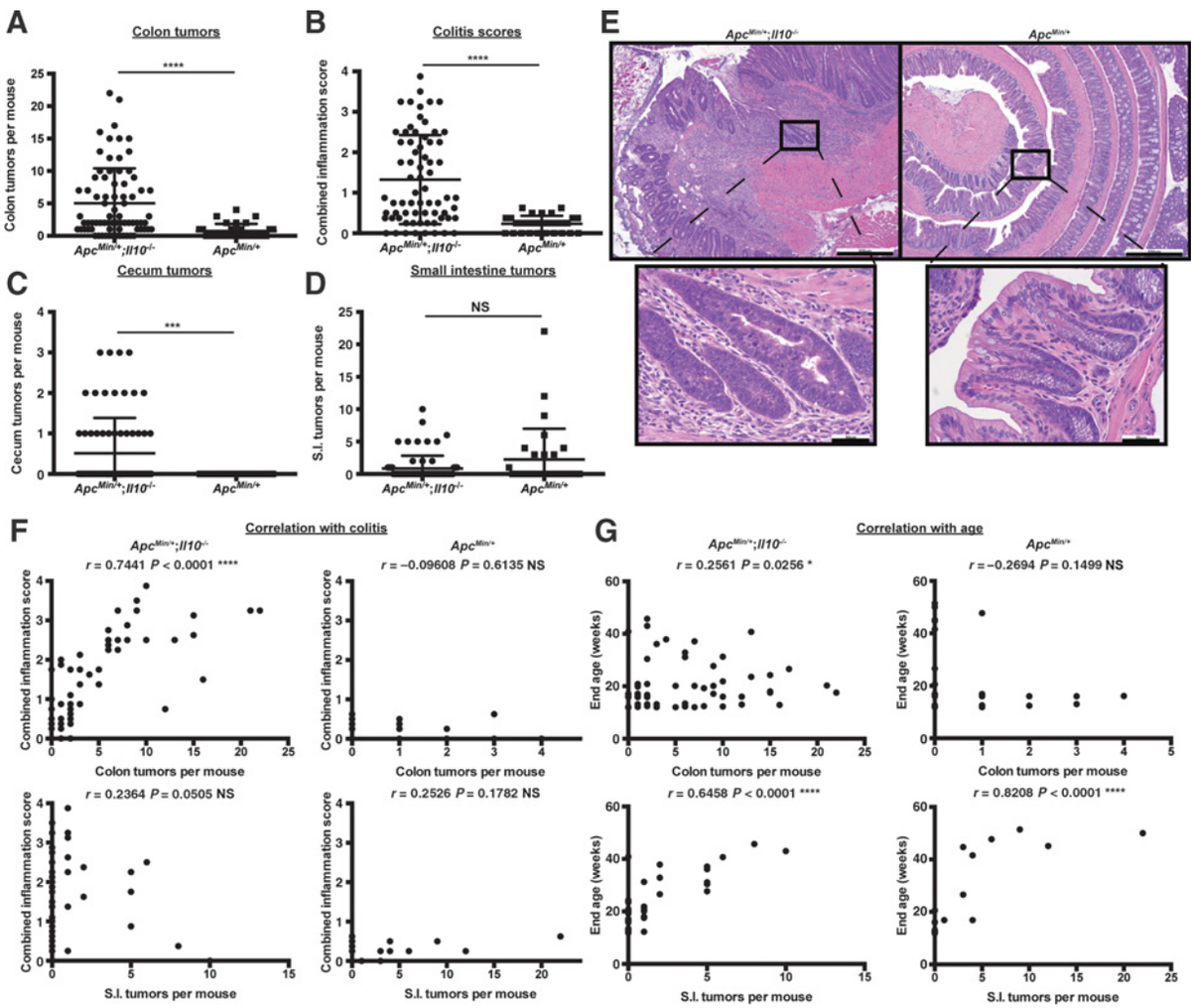

Figure 1.

Inflammation fosters colorectal cancer development in genetically engineered mice. **A,** Macroscopic colon tumor counts from 12 to 51-week-old SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ and *Apc*$^{Min/+}$mice. **B,** Colon combined histologic inflammation scores (the average of the proximal and distal inflammation scores) from SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ and *Apc*$^{Min/+}$mice. **C** and **D,** Cecum and small intestine macroscopic tumor counts from SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ and *Apc*$^{Min/+}$mice. **E,** Colon hematoxylin and eosin stained from 30- to 40-week-old SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ and *Apc*$^{Min/+}$mice (magnification, ×5, ×40). **F,** Relationship between colon inflammation score and macroscopic colon or small intestine tumors in SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ and *Apc*$^{Min/+}$mice. **G,** Relationship between mouse endpoint age and macroscopic tumors in SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ and *Apc*$^{Min/+}$mice. Spearman correlation *r* values and corresponding *P* values are noted in each panel. Data, mean ± SD. Two-tailed Mann–Whitney statistical analysis: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$; ****, $P < 0.0001$; NS, not significant.

qPCR was performed on the CFX384 Touch Real-Time PCR Detection System (1855485, Bio-Rad) using the SsoAdvanced Universal SYBR Green Supermix (1725274, Bio-Rad). The following primers were used: IL6_F CGGAGGCTTGGTTACACATGTT, IL6_R CTGGCTTTGTCTTTCTTGTTATC; TNFα_F ATGAGCACAGAAAGCATGATC, TNFα_R TACAGGCTTGTCACTCGAATT; IFNγ_F ACGCTTATGTTGTTGCTGATGG, IFNγ_R CTTCCTCATGGCTGTTTCTGG; IL1β_F GCCCATCCTCTGTGACTCAT, IL1β_R AGGCCACGGTATTTTGTCG; IL17A_F GCCCTCAGACTACCTCAACC, IL17A_R ACACCCACCAGCATCTTCTC; IL22_F CATGCAGGAGGTGGTGCCTT, IL22_R CAGACGCAAGCATTTCTCAG; 36B4_F TCCAGGCTTTGGGCATCA, 36B4_R CTTTATTCAGCTGCACATCACTCAGA; and GUSB_F CCGATTATCCAGAGCGAGTATG, GUSB_R CTCAGCGGTGACTGGTTCG. 36B4 and Gusb were used as references. Relative fold gene expression was calculated using the delta delta Ct method.

Statistical analysis

Data are expressed as mean ± standard deviation. Significance thresholds of ****, $P < 0.0001$; ***, $P < 0.001$; **, $P < 0.01$; *, $P < 0.05$, or NS: not significant ($P > 0.05$) are shown. Statistics for all figures except for the 16S rRNA sequencing analysis were calculated with GraphPad Prism using the Mann–Whitney nonparametric unpaired two-tailed *t* test. For correlational analyses, the Spearman nonparametric correlation analysis with a confidence interval of 95% and a two-tailed significance test with alpha = 0.05 was used.

Data availability

All sequences have been uploaded to the NCBI SRA (National Center for Biotechnology Information Sequence Read Archive) under BioProject PRJNA350319. See Supplementary Table S3 for individual accession numbers.

Results

Inflammation promotes development of colorectal cancer in $Apc^{Min/+}$;$Il10^{-/-}$ mice

To investigate the interaction between inflammation and colorectal cancer development, we interbred $Il10^{-/-}$ mice to $Apc^{Min/+}$ mice (129SvEV background) to generate $Apc^{Min/+}$;$Il10^{-/-}$ mice. Colon and cecal tumors increased dramatically in $Apc^{Min/+}$;$Il10^{-/-}$ compared with $Apc^{Min/+}$ mice (colon tumor mean= 5.03 vs. 0.73, respectively $P < 0.0001$; cecal tumor mean = 0.51 vs. 0, respectively, $P < 0.0005$; Fig. 1A and C), whereas small bowel lesions remained similar between the two genotypes (mean = 0.84 vs. 2.23 $P = 0.2914$; Fig. 1D). Histological assessment showed presence of colonic neoplastic lesions in $Apc^{Min/+}$;$Il10^{-/-}$ mice (Fig. 1E) and, as expected, increased inflammation in $Apc^{Min/+}$;$Il10^{-/-}$ mice compared to $Apc^{Min/+}$ mice (combined score mean = 1.32 vs. 0.23, respectively, $P < 0.0001$; Fig. 1B). There was a significant correlation between development of colorectal cancer and extent of colon inflammation in $Apc^{Min/+}$;$Il10^{-/-}$ mice ($r = 0.7441$; $P < 0.0001$), whereas no such correlation is observed in $Apc^{Min/+}$ mice ($r = -0.09608$; $P = 0.6135$; Fig. 1F). Furthermore, development of small intestinal neoplasia did not correlate with the state of colitis in either model ($Apc^{Min/+}$;$Il10^{-/-}$, $r = 0.2364$; $Apc^{Min/+}$, $r = 0.2526$; $P > 0.05$; Fig. 1F). Interestingly, endpoint age (see Materials and Methods for description of the chosen endpoint age range) was a significant contributor to tumorigenesis in the small bowel of both $Apc^{Min/+}$;$Il10^{-/-}$ and $Apc^{Min/+}$ mice ($r = 0.6458$, 0.8208, respectively, $P < 0.0001$) but only weakly contributed to neoplasia in the large bowel of $Apc^{Min/+}$;$Il10^{-/-}$ mice ($r = 0.2561$; $P = 0.0256$; Fig. 1G). Thus, genetic susceptibility to inflammation promotes colon but not small intestinal tumorigenesis in SPF $Apc^{Min/+}$;$Il10^{-/-}$ mice, while age appears to be the primary factor contributing to small intestinal tumorigenesis in SPF $Apc^{Min/+}$;$Il10^{-/-}$ and $Apc^{Min/+}$ mice.

Due to its role in promoting cellular proliferation, we evaluated the distribution of nuclear catenin beta 1 (CTNNB1) and proliferating cell nuclear antigen (PCNA) in actively inflamed and neoplastic regions of $Apc^{Min/+}$;$Il10^{-/-}$ and $Apc^{Min/+}$ colons. Nuclear CTNNB1 and PCNA staining was mostly restricted to the crypt bases in $Apc^{Min/+}$ mice (Fig. 2B and D; Supplementary Fig. S2B and S2D). In contrast, the colonic mucosa from $Apc^{Min/+}$;$Il10^{-/-}$ mice showed areas of CTNNB1 and PCNA staining extending the full crypt length in dysplastic regions (Fig. 2A and C; Supplementary Fig. S2A and S2C). In addition, expression of proliferative and inflammatory IL6, TNFα, IFNγ, IL1β, IL22, and IL17a mRNA increased in $Apc^{Min/+}$;$Il10^{-/-}$ compared with $Apc^{Min/+}$proximal colon tissues (Fig. 2E). Furthermore, $Apc^{Min/+}$;$Il10^{-/-}$ mice with a high number of tumors (>2) had significantly increased levels of TNFα, IFNγ, and IL1β mRNA compared to low tumor number (≤2) $Apc^{Min/+}$;$Il10^{-/-}$ mice (Fig. 2F). Taken together, these data suggest that the heightened inflammatory and proliferative state observed in $Apc^{Min/+}$;$Il10^{-/-}$ compared with $Apc^{Min/+}$ mice increased propensity for colorectal tumor formation and progression.

Differential microbial composition within $Apc^{Min/+}$;$Il10^{-/-}$ mice correlates with tumor multiplicity and inflammation status

We previously showed that inflammation altered microbial composition (17), a condition important for colorectal cancer development. Using 16S rRNA sequencing, we found that the SPF $Apc^{Min/+}$;$Il10^{-/-}$ stool microbiome was associated with both colon inflammation score and tumor number (Fig. 3A), especially along the first principal coordinates analysis (PCoA) axis (Fig. 3B). Using mixed linear models with either colon tumor number or colitis score as the independent variable, we identified 17 genera significantly affected by both colon tumor number and colitis score, including *Allobaculum*, *Anaerotruncus*, *Butyrivibrio*, *Clostridium IV*, *Clostridium XI*, *Enterococcus*, *Oscillibacter*, *Pseudoflavonifractor*, and *Syntrophococcus* (Fig. 3C; Supplementary Table S2). Only 5 genera were affected by colon tumor number but not combined inflammation score (*Akkermansia*, *Coprobacillus*, *Escherichia/Shigella*, *Marvinbryantia* and *Robinsoniella*) while 4 genera were only affected by combined inflammation score and not colon tumor number (*Alistipes*, *Enterorhabdus*, *Flavonifractor*, and *Roseburia*; Fig. 3C). Interestingly, approximately 1/3 of these genera (10/26) were significantly increased in mice with colon tumors and/or inflammation while approximately 2/3 were decreased (16/26). Therefore, the microbial community composition is correlated with higher tumor numbers and inflammation, suggesting specific bacteria play a role in the development of colon inflammation and tumorigenesis in $Apc^{Min/+}$;$Il10^{-/}$ mice.

Bacteria are essential for development of colon tumorigenesis in $Apc^{Min/+}$;$Il10^{-/-}$mice

To stringently evaluate the impact of bacteria on colorectal cancer development, we derived $Apc^{Min/+}$;$Il10^{-/-}$ and $Apc^{Min/}$

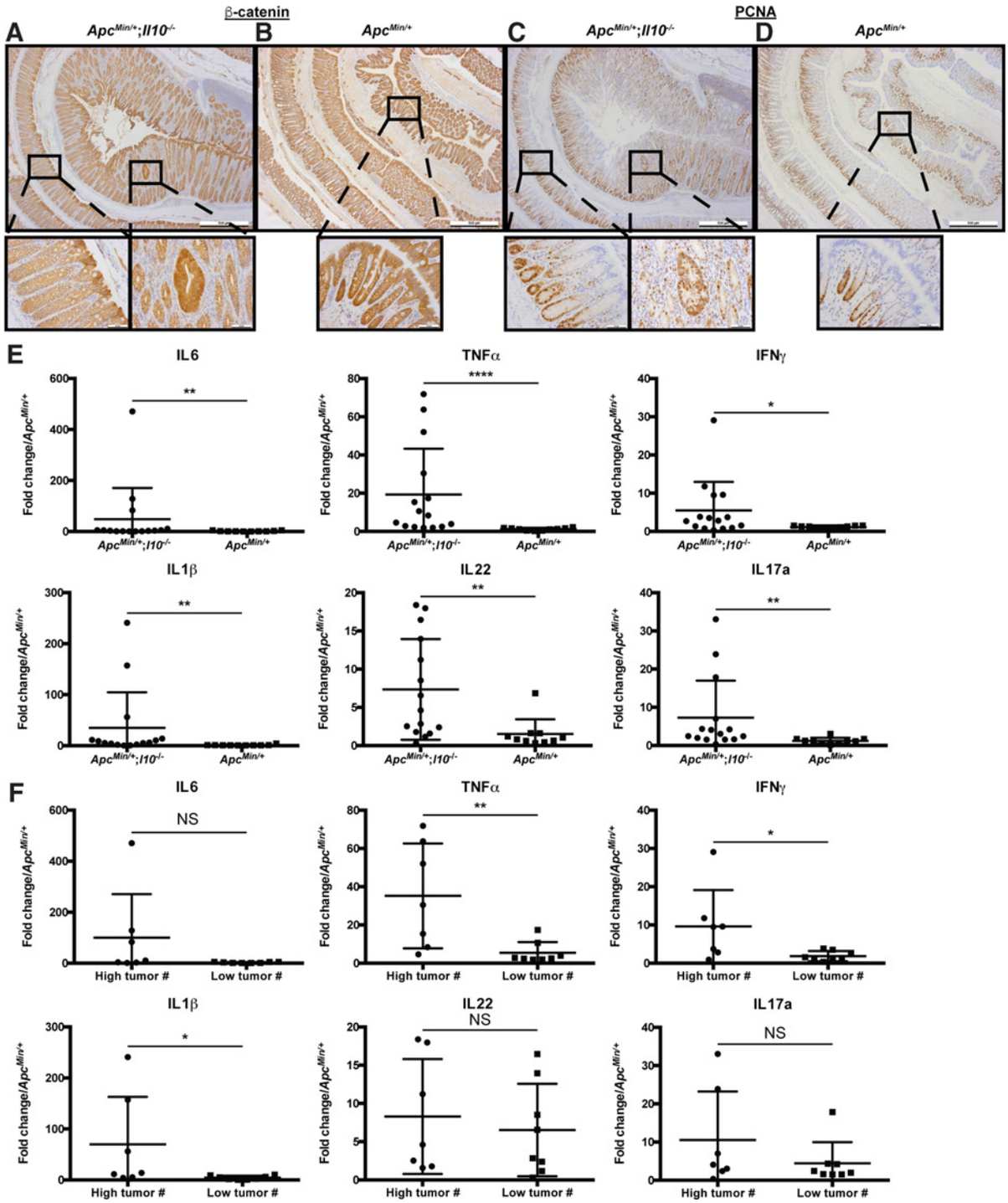

Figure 2.

Apc$^{Min/+}$;*Il10*$^{-/-}$ mice have increased colon proliferation and inflammation. **A–B,** CTNNB1 IHC from approximately 16-week-old SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ (**A**) and *Apc*$^{Min/+}$(**B**) colons. **C–D,** PCNA IHC from SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ (**C**) and *Apc*$^{Min/+}$(**D**) colons. Higher magnification of both dysplastic and normal regions is shown for SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$mice. **E,** IL6, TNFα, IFNγ, IL1β, IL22, and IL17a mRNA expression in 16–48-week-old SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ and *Apc*$^{Min/+}$proximal colon tissue snips, with relative fold expression compared to *Apc*$^{Min/+}$mice. **F,** IL6, TNFα, IFNγ, IL1β, IL22, and IL17a mRNA expression in 16–48-week-old SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ stratified by tumor number (high: > 2 tumors or low: ≤ 2 tumors), with relative fold expression compared to *Apc*$^{Min/+}$mice. Data, mean ± SD. Two-tailed Mann–Whitney statistical analysis: *, $P < 0.05$; **, $P < 0.01$; ****, $P < 0.0001$; NS, not significant.

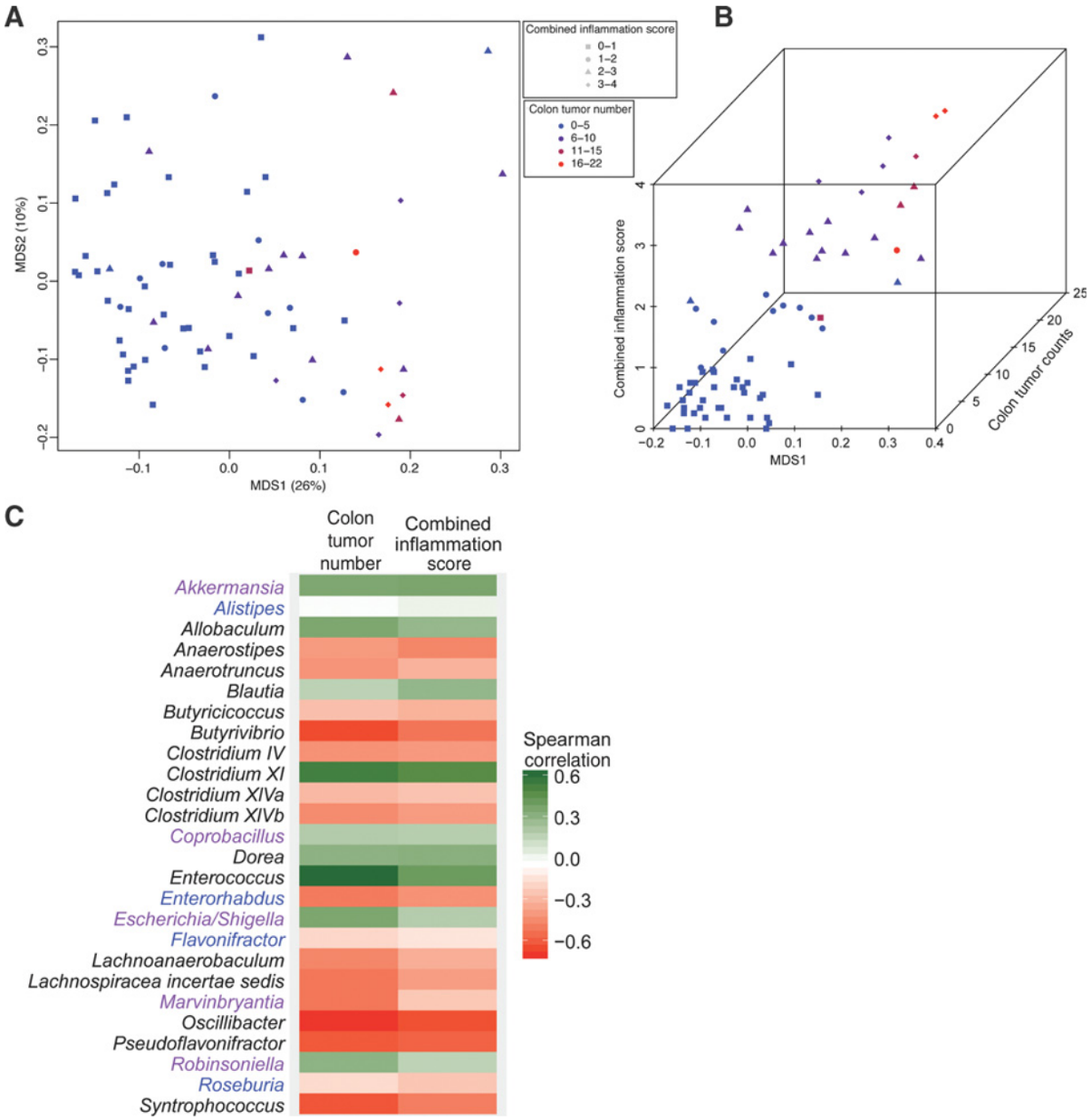

Figure 3.

SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ with colon tumors and colitis have an altered stool microbiota. **A,** PCoA comparing the stool microbial composition of SPF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ mice. Each symbol represents an individual mouse (n = 70) with symbol shape and color according to colon inflammation score and tumor number, respectively. **B,** 3D plot showing how MDS1 from the PCoA (*x*-axis) varies with combined inflammation score (*y*-axis) and colon tumor number (*z*-axis). **C,** Heatmap depicting the Spearman correlations (positive correlations, green; negative correlations, red) for genera that are significantly associated with colon tumor number and/or colitis in *Apc*$^{Min/+}$;*Il10*$^{-/-}$ mice. Genera significant for both colon tumor number and combined inflammation score are in black font, colon tumor number only in purple font, and combined inflammation score only in blue font.

$^{+}$mice in GF conditions and then performed microbial manipulation by either gavaging the mice with SPF biota or allowing them to naturally acquire a microbiota in SPF conditions. Importantly, colon tumorigenesis was practically abolished in GF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ mice (mean = 0) compared with SPF conditions (Fig. 4A, D). Interestingly, SPF gavage enhanced colon tumor loads compared to passive SPF colonization of *Apc*$^{Min/+}$;*Il10*$^{-/-}$ mice (mean = 3.86 vs. 1, respectively, $P = 0.0126$; Fig. 4A and D), although colitis scores and most proliferative/inflammatory cytokine expression (IL6, TNFα, IFNγ, IL22, and IL17a) were not significantly different (colitis score means = 1.86 vs. 2.36 respectively, $P = 0.46$; Figs. 4B and 5D). Colon inflammation and tumors were negligible or absent in GF and SPF gavaged *Apc*$^{Min/+}$mice (Supplementary Fig. S3A and S3B), suggesting inflammation is a key component of bacteria-mediated colon tumorigenesis. Development of small bowel neoplasia in *Apc*$^{Min/+}$;*Il10*$^{-/-}$ and

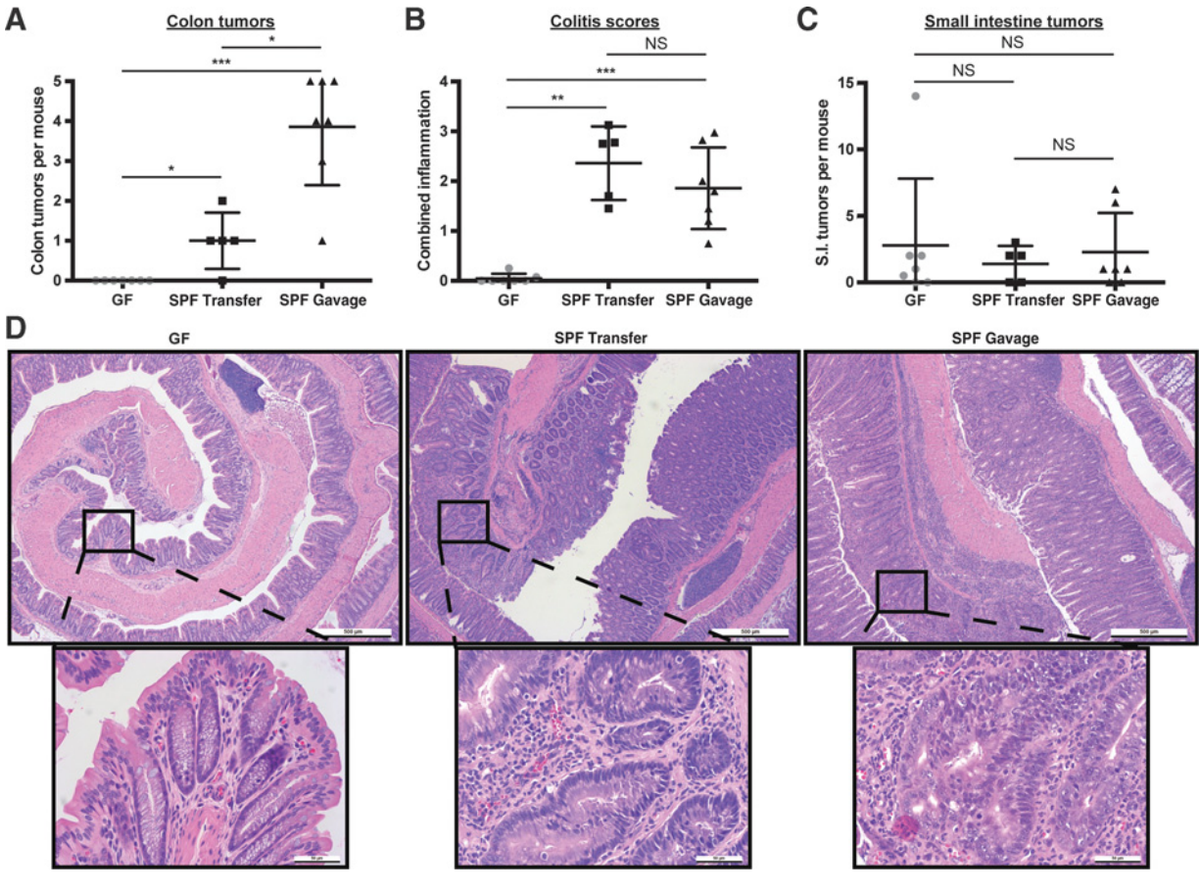

Figure 4.

Bacteria promote distal colon inflammation and tumorigenesis in $Apc^{Min/+}$;$Il10^{-/-}$ mice. **A–C,** Colon macroscopic tumor counts (**A**), colitis scores (**B**), and small intestine tumor counts (**C**) from GF ($n = 7$), SPF-transferred ($n = 5$), and SPF-gavaged ($n = 7$) $Apc^{Min/+}$;$Il10^{-/-}$ mice. SPF transfer (transferred to SPF and allowed to naturally acquire their microbiota) and gavage (transferred to SPF and gavaged with the cecal and fecal contents from a wild-type 129SvEv mouse) mice were sacrificed 16 weeks after transfer from GF. **D,** Colon hematoxylin and eosin stained from GF, SPF-transferred, and SPF-gavaged $Apc^{Min/+}$;$Il10^{-/-}$ mice. Data, mean ± SD. Two-tailed Mann–Whitney statistical analysis: *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$; NS, not significant.

$Apc^{Min/+}$mice (Fig. 5C; Supplementary Fig. S3C) was not significantly impacted by microbial colonization, suggesting a less pronounced role for the microbiota in the small intestine compared to the colon in this model. GF $Apc^{Min/+}$;$Il10^{-/-}$ colons had reduced nuclear CTNNB1 and PCNA (Fig. 5A–C; Supplementary Fig. S4A–S4C) and decreased inflammatory cytokine expression (Fig. 5D) compared to SPF mice, indicating bacteria play a significant role in the increased inflammatory and proliferative state in SPF $Apc^{Min/+}$;$Il10^{-/-}$ colons.

Gnotobiotic experiments reveal specific microbial requirements for colorectal cancer development in $Apc^{Min/+}$;$Il10^{-/-}$mice

Fusobacterium spp. have been linked to the development of colorectal cancer (4) and recent studies showed increased carcinogenesis in *F. nucleatum*-colonized $Apc^{Min/+}$ mice (23–25). To investigate the interplay between microbiota and *F. nucleatum* in colorectal cancer, we transferred GF $Apc^{Min/+}$ to SPF conditions and gavaged them with SPF microbiota followed by weekly gavage with a $fadA^{+}$, $fap2^{-}$*F. nucleatum* colorectal cancer clinical isolate for 20 weeks. Interestingly, and in contrast to previous studies (23–25), the presence of *F. nucleatum* failed to enhance carcinogenesis in these mice (Fig. 6A and C). We next transferred GF $Apc^{Min/+}$;$Il10^{-/-}$ mice to SPF conditions, gavaged them with SPF microbiota, and then introduced a mixture of 6 *F. nucleatum* strains ($fadA^{+}$, $fap2^{-}$ or +) obtained from colorectal cancer patients by weekly gavage for 16 weeks. Although $Apc^{Min/+}$;$Il10^{-/-}$ mice developed more inflammation and tumors than $Apc^{Min/+}$ mice, presence of *F. nucleatum* species did not influence intestinal carcinogenesis or colitis (Fig. 6B and C). To rule out the possibility that the SPF biota downmodulates *F. nucleatum* carcinogenic properties, we transferred GF $Apc^{Min/+}$ mice to a gnotobiotic isolator and associated these mice with a mixture of 6 *F. nucleatum* colorectal cancer clinical isolates ($fadA^{+}$, $fap2^{-}$ or +; single gavage). Again, the presence of *F. nucleatum* isolates failed to enhance intestinal carcinogenesis in $Apc^{Min/+}$ mice (Fig. 6D) despite the presence of high colony-forming unit (CFU) counts (mean = 10^{7} CFU/g of stool). Although we did not see evidence of histological inflammation, to further confirm the effect of *F. nucleatum* on host inflammatory response, we examined inflammatory cytokine gene expression via qPCR. We found comparable

levels of TNFα and IL1β in the mouse distal colon between germ-free and monoassociated $Apc^{Min/+}$ mice, whereas IL6, IFNγ, IL22, and IL17a levels were undetectable (data not shown).

To further study the relationship between microbial status and carcinogenesis in gnotobiotic $Apc^{Min/+}$;$Il10^{-/-}$ mice, we colonized these mice with *E. coli* NC101, a strain producing the colibactin

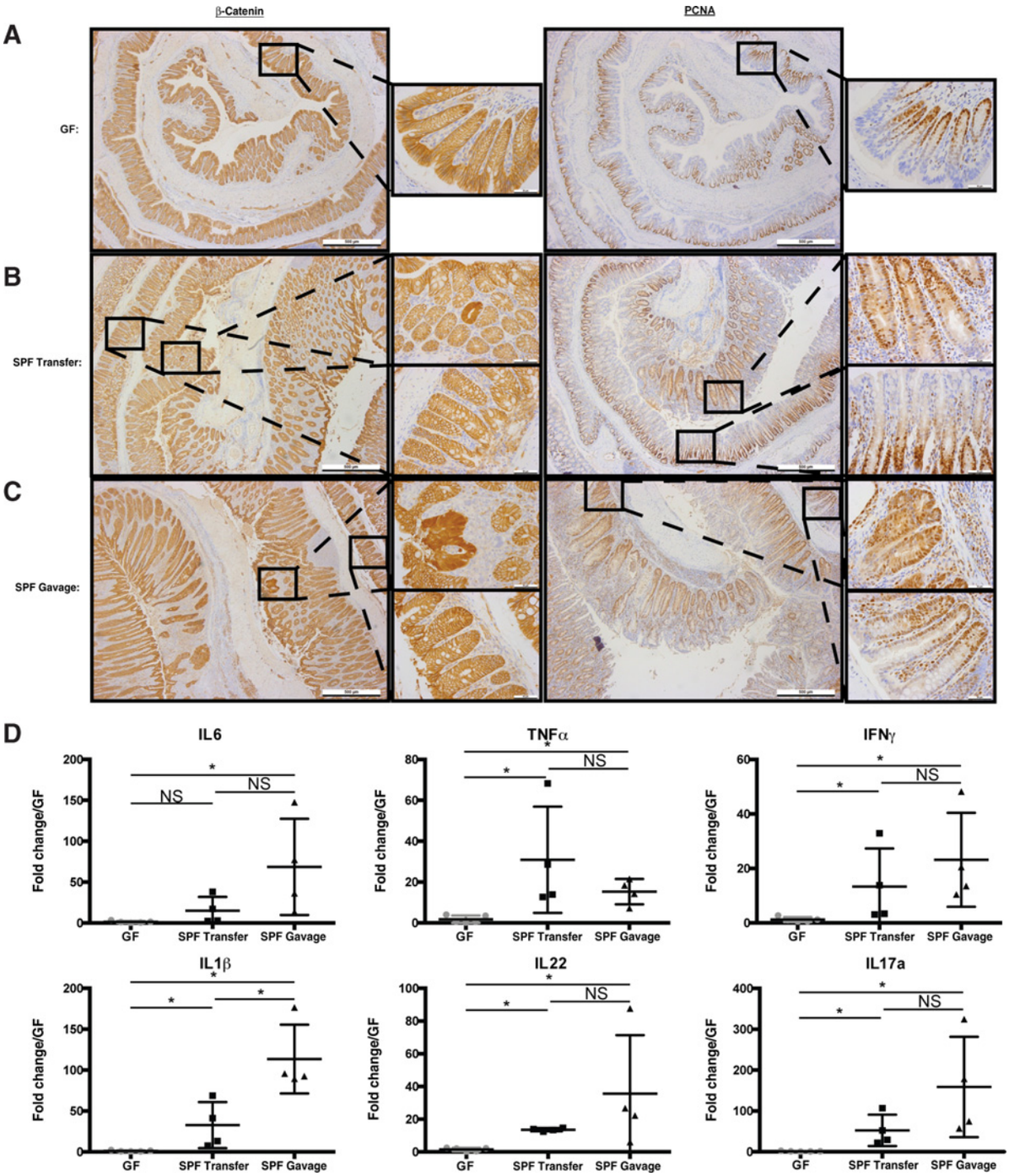

Figure 5.

Microbiota promote colon inflammation and proliferation in $Apc^{Min/+}$;$Il10^{-/-}$ mice. **A–C,** β-Catenin and PCNA IHC from GF (**A**), SPF-transferred (**B**), and SPF-gavaged (**C**) $Apc^{Min/+}$;$Il10^{-/-}$ distal colons. Higher magnification of both dysplastic and normal regions are shown for SPF transfer and gavage $Apc^{Min/+}$;$Il10^{-/-}$ mice. **D,** IL6, TNFα, IFNγ, IL1β, IL22, and IL17a mRNA expression in GF ($n = 5$), SPF-transfer ($n = 4$), and SPF-gavaged ($n = 4$) $Apc^{Min/+}$;$Il10^{-/-}$ proximal colon tissue snips, with relative fold expression compared to GF. Data, mean ± SD. Two-tailed Mann–Whitney statistical analysis: *, $P < 0.05$; NS, not significant.

genotoxin. We previously showed that removing *pks* from *E. coli* NC101 decreased development of colorectal cancer in the azoxymethane (AOM)/*Il10*$^{-/-}$ mouse model (17). We next mono-associated *Apc*$^{Min/+}$;*Il10*$^{-/-}$ mice by oral gavage (10^8 CFU/mouse) with an *E. coli* NC101 mutant deficient for *clbP*, the *pks* gene necessary for colibactin activation (Δ*clbP*). We found that wild-type NC101-colonized mice developed significantly more colon tumors than *E. coli* NC101 Δ*clbP*-associated mice (mean = 1.71 vs. 0.17, respectively, $P = 0.0023$; Fig. 7A). The finding that NC101 Δ*clbP* has diminished carcinogenic capacity compared to NC101 was confirmed in the AOM/*Il10*$^{-/-}$ model (mean = 2 vs. 5 tumors, respectively, $P = 0.039$; Supplementary Fig. S5). Importantly,

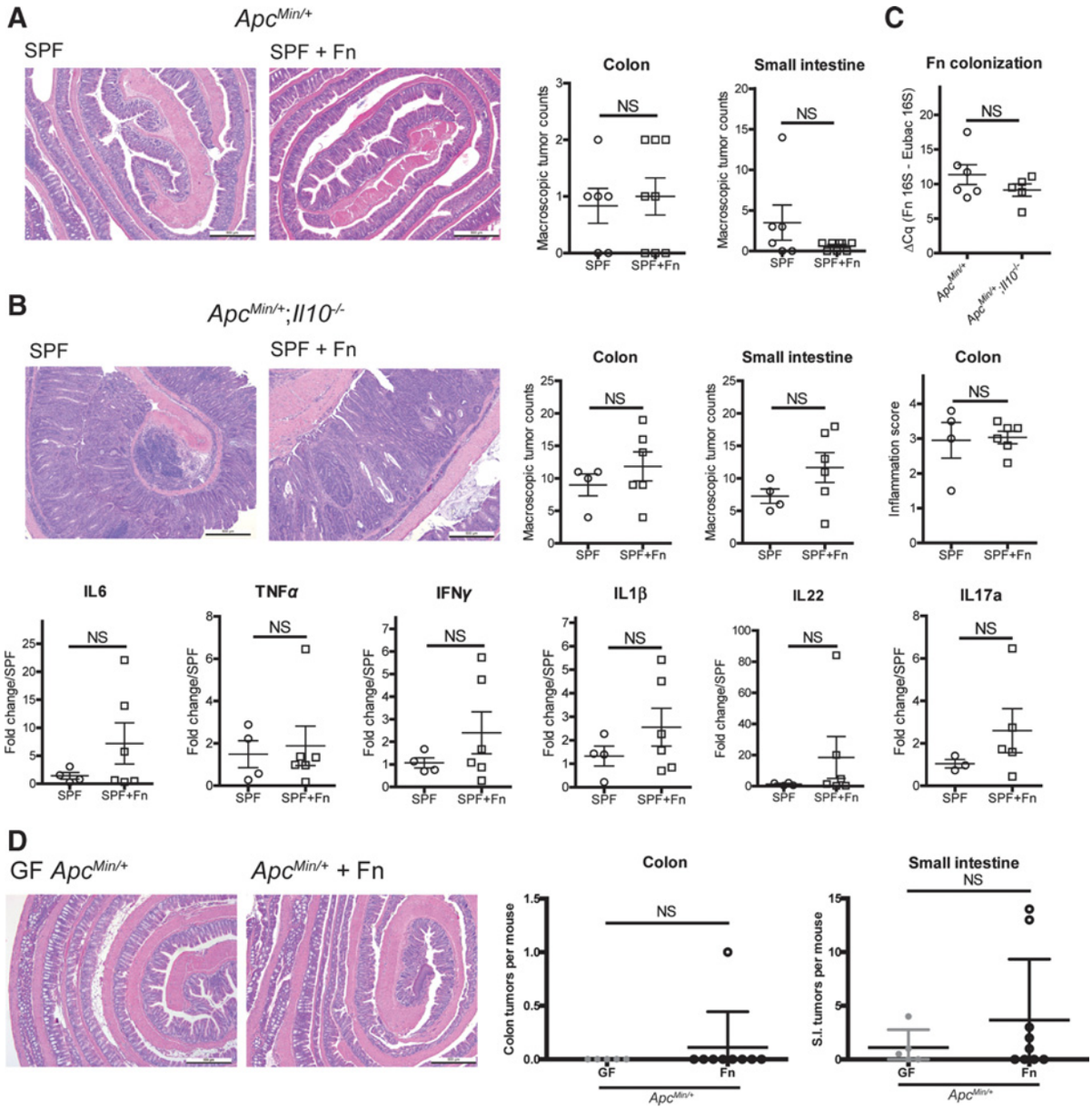

Figure 6.

F. nucleatum (Fn) does not exhibit proinflammatory and protumorigenic activities. **A,** GF *Apc*$^{Min/+}$ mice were transferred to SPF conditions and immediately gavaged with SPF microbiota ($n = 6$). SPF + Fn mice ($n = 8$) received Fn (a single strain human colorectal cancer isolate) via weekly gavage. SPF (control) mice received weekly gavage of BHI medium. Tumorigenesis was examined 20 weeks later. **B,** GF *Apc*$^{Min/+}$;*Il10*$^{-/-}$ mice were transferred to SPF conditions and immediately gavaged with SPF microbiota ($n = 4$). SPF + Fn mice ($n = 6$) received Fn (a mixture of 6 human colorectal cancer isolates) via weekly gavage. SPF (control) mice received weekly gavage of BHI medium. Tumorigenesis and inflammation were examined 16 weeks later (top). IL6, TNFα, IFNγ, IL1β, IL22, and IL17a mRNA expression in SPF and SPF + Fn *Apc*$^{Min/+}$;*Il10*$^{-/-}$ distal colon snips (bottom). **C,** qPCR examination of fecal Fn levels in SPF + Fn *Apc*$^{Min/+}$ and *Apc*$^{Min/+}$;*Il10*$^{-/-}$ mice. **D,** GF *Apc*$^{Min/+}$ mice were transferred to a gnotobiotic isolator and gavaged with Fn (a mixture of 6 human colorectal cancer isolates). Tumorigenesis was examined 16 weeks later (GF $n = 5$ and Fn colonized $n = 9$). In **A**, **B**, and **D**, representative histology images of the colon are shown on the left. Macroscopic tumor counts are shown on the right. Data, mean ± SD. Two-tailed Mann–Whitney statistical analysis: NS, not significant.

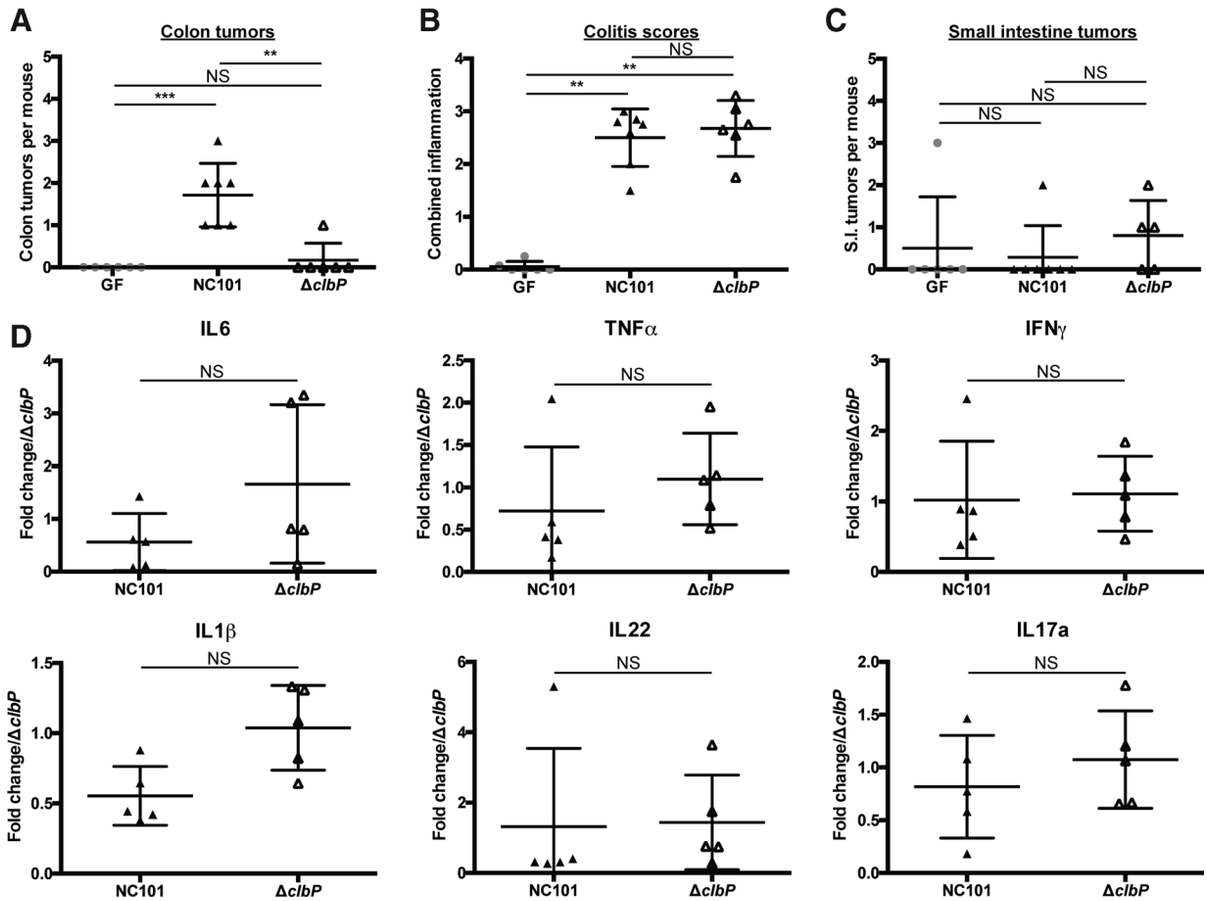

Figure 7.

Colibactin promotes colorectal cancer development in $Apc^{Min/+}$;$Il10^{-/-}$mice. **A–C,** Colon tumor counts (**A**), colitis scores (**B**), and small intestine tumor counts (**C**) from GF $Apc^{Min/+}$;$Il10^{-/-}$ ($n = 6$) and 16 week *E. coli* NC101 ($n = 7$) or Δ*clbP* ($n = 6$) monoassociated $Apc^{Min/+}$;$Il10^{-/-}$ mice. **D,** IL6, TNFα, IFNγ, IL1β, IL22, and IL17a mRNA expression in NC101 ($n = 5$) or Δ*clbP* ($n = 5$) monoassociated $Apc^{Min/+}$;$Il10^{-/-}$ distal colon snips with relative fold expression compared with Δ*clbP* monoassociated $Apc^{Min/+}$; $Il10^{-/-}$ mice. Data, mean ± SD. Two-tailed Mann–Whitney statistical analysis: **, $P < 0.01$; ***, $P < 0.001$; NS, not significant.

deletion of *clbP* did not compromise the ability of *E. coli* NC101 to induce inflammation (colitis score mean = 2.675, 2.5 respectively; $P = 0.76$; Fig. 7B and D). Presence of a functional *pks* did not influence development of small intestinal tumors in $Apc^{Min/+}$;$Il10^{-/-}$ mice (mean = 0.29, 0.8, respectively; $P = 0.22$; Fig. 7C). Overall, these findings show that $Apc^{Min/+}$;$Il10^{-/-}$ mice are sensitive to microbial status and develop site specific tumors, with colibactin-producing *E. coli* but not $fadA^{+}$, $fap2^{-/+}$ *F. nucleatum* enhancing colon tumor development.

Discussion

Genetics and environmental factors play an important role in colorectal cancer development, with increasing attention directed toward the intestinal microbiota as a key environmental component (26). In general, the microbiota is thought to play a procarcinogenic role in colorectal cancer with numerous colorectal cancer mouse models demonstrating tumor reduction in antibiotic treated or GF mice (27). Here we utilized gnotobiotic $Apc^{Min/+}$and $Apc^{Min/+}$;$Il10^{-/-}$ mice to define the relationship between inflammation, microbial status, and tumorigenesis. We observed that despite genetic susceptibility in both $Apc^{Min/+}$and $Apc^{Min/+}$;$Il10^{-/-}$ mice, colonic inflammation in the latter mice fosters development of colon tumors, which was associated with an altered luminal microbiota composition. Gnotobiotic experiments revealed that *E. coli* colibactin but not *F. nucleatum* FadA and Fap2 adhesins promote colon tumorigenesis, suggesting an intricate interaction between host genetics and bacteria.

We observed an inflammation-dependent increase in colon tumorigenesis in 129 SvEv $Apc^{Min/+}$;$Il10^{-/-}$ mice, which is in line with previous reports on *Il10*-deficient C57BL/6 $Apc^{Min/+}$ and $Apc^{\Delta 468}$ mice (13, 14). However, in the small intestine compartment, tumors developed at a comparable rate regardless of *Il10* status in $Apc^{Min/+}$ mice, which is in contrast to previous findings showing a delay in small intestinal polyp formation in *Il10* deficient $Apc^{\Delta 468}$ mice (15). Possible explanations for the differences in small intestine tumor formation may be due to genetic background differences that have been shown to strongly modulate tumor multiplicity, particularly in the small intestine of $Apc^{Min/+}$mice (28). Nevertheless, our findings that $Apc^{Min/+}$;$Il10^{-/-}$and $Apc^{Min/+}$ small intestine tumor development significantly correlated with age but not

inflammation suggest that age-related factors are a primary driver of small intestinal tumorigenesis

We observed changes in the abundance of 26 genera that correlated with colon inflammation and/or tumor number. In contrast to previous sequencing results with $Apc^{Min/+}$ and T cell–specific $Apc^{Min/+}$;$Il10^{-/-}$mice, no significant increases in the *Bacteroides* or *Porphyromonas* genera were observed (14). These differences are likely due to a combination of factors including sampling location (stool vs. tissue), mouse genetic background, husbandry and 16S sequencing methods (V1–V3 region vs. V3–V4). Importantly, *Akkermansia*, *Blautia*, *Dorea*, *Enterococcus*, and *Escherichia/Shigella*, which positively correlated with tumor number, have been previously associated as increased in mucosal tissue (17, 29, 30) or stools from either human colorectal cancer patients (31–33) or AOM/DSS mice (34, 35). Conversely, some of the genera that negatively correlated with tumors and inflammation or just inflammation included *Clostridium XIVa*, *Lachnospiracea* and *Roseburia*, which have been implicated as butyrate producers and were decreased in colorectal cancer stool (31, 33) or stools from AOM/DSS mice transplanted with stools from human patient samples (34). Thus, our sequencing results suggest there are changes in the microbiota that are associated with colon inflammation and tumor status.

The interaction between bacteria and the host in the context of intestinal carcinogenesis is complex. One study, using the chemical AOM/DSS regimen, reported that GF mice developed more colonic tumors than mice colonized with a complex biota, suggesting certain bacteria can have a beneficial role in colorectal cancer (36). Because microbial composition is a key determinant of colon tumor burden in AOM/DSS mice (35, 37), this chemical model may better capture the protective functions of bacteria than the genetic $Apc^{Min/+}$mouse model.

Nevertheless, the role of bacteria in $Apc^{Min/+}$intestinal tumorigenesis is complex, with one report showing fewer tumors in the middle region of the small intestine in GF $Apc^{Min/+}$mice (9) while another report showed reduced tumors throughout the intestine in GF $Apc^{Min/+}$mice (10). The difference in tumor distribution is not clear. Our finding that bacteria promote colon tumors in $Apc^{Min/+}$;$Il10^{-/-}$mice is in line with a study showing reduced colon polyp numbers in $Apc^{\Delta 468}$;$CD4^{Cre}Il10^{f/f}$ mice following broad-spectrum antibiotic treatment (14).

Numerous studies have implicated *Fusobacterium* spp., in particular *F. nucleatum*, as carcinogenic, based on associative studies showing the presence of the bacterium in the luminal and mucosal compartment of human colorectal cancer patients using genomic analyses (3, 4, 24, 33). In addition, daily gavage of *F. nucleatum* (strain EAVG_002; 7/1 or ATCC 25586) for 8–24 weeks was shown to promote intestinal tumorigenesis in C57BL/6 $Apc^{Min/+}$mice (23–25). Surprisingly, $Apc^{Min/+}$ and $Apc^{Min/+}$;$Il10^{-/-}$mice colonized with $fadA^{+}$, $fap2^{+/-}$*F. nucleatum* isolates from colorectal cancer patients failed to promote intestinal tumorigenesis, in the presence (SPF) or absence of complex biota (gnotobiotic). The absence of tumorigenesis in monoassociated $Apc^{Min/+}$mice was not due to poor colonization, because a high load of *F. nucleatum* (10^7 CFU/g) was recovered from these mice. The discrepancy between our study and previous *F. nucleatum* $Apc^{Min/+}$studies (23–25) is unclear but could be the result of strain specific properties (EAVG_002; refs. 19, 38) and ATCC 25586 (39, 40) vs. strains tested here), mouse genetic background differences and different microbial environments, as microbial communities are notoriously different between institutions. Nevertheless, our gnotobiotic approach clearly showed that presence of FadA and Fap2 adhesins in *F. nucleatum* is not sufficient to induce either inflammation or cancer, as opposed to *E. coli* pks^{+} monoassociated $Apc^{Min/+}$;$Il10^{-/-}$mice. Thus, it is possible that only a select group of *F. nucleatum* strains possess carcinogenic abilities, which require interactions with other specific members of the microbial community. It will be important to define these interactions and test a larger set of *F. nucleatum* strains to determine the role of these bacteria in colorectal cancer pathogenesis.

Several studies have found an association between pks^{+}*E. coli* and human colorectal cancer patients (17, 29). Furthermore, pks^{+}*E. coli* isolates from mice or human colorectal cancer patients have a protumorigenic effect in GF AOM/$Il10^{-/-}$, SPF $Apc^{Min/+}$, and SPF AOM/DSS mice (17, 29, 41). However, because the *pks*-associated *clbA* gene is implicated in the production of siderophores located in the enterobactin (*ent*) and yersiniabactin (HPI) loci (42), and our previous observation was based on removal of the entire *pks* island, it was unclear whether the decreased tumorigenesis observed in AOM/$Il10^{-/-}$ mice was the consequence of dual siderophore/colibactin impairment, or solely due to abolished *pks* activity. Using a mutant with defective ClbP, the key enzyme implicated in pre-colibactin cleavage and generation of the active form (43), we demonstrated the colibactin-producing *E. coli* murine isolate NC101 is responsible for the protumorigenic effect of the bacterium in $Apc^{Min/+}$;$Il10^{-/-}$ mice. Whether *clbA* contributes to colibactin-mediated tumorigenesis is still unclear and would need to be investigated, especially because a recent *in vitro* study showed that iron levels and *E. coli* iron sensors regulate *clbA* transcription and colibactin production (44). Because our studies were performed using a monoassociation approach, and therefore without competitive pressure from other microorganisms, the full extent of iron acquisition on *E. coli* pks^{+} induced carcinogenesis remains unclear.

Recent studies have attempted to dissect the contributions of intrinsic (organ specific stem cell division rates, aging) and extrinsic factors (hereditary mutations, lifestyle, environmental exposure, etc.), to overall cancer risk in humans (45–47). However, the interplay between all these factors makes it difficult to tease out the various contributions using epidemiological data. Nevertheless, these studies suggest that small intestine cancers with a relatively low lifetime risk are driven by intrinsic risk factors, while 82.9% of the mutation signatures in colorectal cancers are from extrinsic factors, correlating with a much higher lifetime risk (46). We postulate that one of the extrinsic factors contributing to colorectal cancer risk is the microbiota, which not coincidentally is also affected by lifestyle and environmental factors (48, 49). Interestingly, the concentration of bacteria increases along the gastrointestinal tract with 10^3–10^4 bacteria/mL in the small intestine to 10^{11} bacteria/mL in the colon, mirroring the distribution of cancer risk along the human intestinal tract (50). Similarly, in the $Apc^{Min/+}$;$Il10^{-/-}$ model, age strongly correlates with small intestine tumor numbers while inflammation and bacteria composition play a strong role in colon tumorigenesis. Elucidating the mechanisms by which specific bacteria interact with other microbiota members to promote carcinogenesis will generate important insights into the pathophysiology of colorectal cancer.

Authors' Contributions

Conception and design: S. Tomkovich, Y. Yang, M. Mohamadzadeh, E. Oswald, C. Jobin
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Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): S. Tomkovich, Y. Yang, J. Gauthier, X. Sun, X. Liu, C. Jobin
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): S. Tomkovich, Y. Yang, K. Winglee, A.A. Fodor, C. Jobin
Writing, review, and/or revision of the manuscript: S. Tomkovich, Y. Yang, K. Winglee, M. Mohamadzadeh, G.P. Wang, E. Oswald, A.A. Fodor, C. Jobin
Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): J. Gauthier
Study supervision: C. Jobin
Other (scored and evaluated histology): M. Mühlbauer
Other (financial contribution): C. Jobin

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