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**Microbiome and colorectal carcinogenesis: Linked mechanisms and racial differences**

Tortora SC *et al*. Microbiome and colorectal cancer

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**Abstract**

Various studies have shown the interplay between the intestinal microbiome, environmental factors, and genetic changes in colorectal cancer (CRC) development. In this review, we highlight the various gut and oral microbiota associated with CRC and colorectal adenomas, and their proposed molecular mechanisms in relation to the processes of “the hallmarks of cancer”, and differences in microbial diversity and abundance between race/ethnicity. Patients with CRC showed increased levels of *Bacteroides, Prevotella, Escherichia coli,*enterotoxigenic *Bacteroides fragilis,Streptococcus gallolyticus,**Enterococcus faecalis,Fusobacterium nucleatum* (*F. nucleatum*) and *Clostridium difficile*. Higher levels of *Bacteroides* have been found in African American (AA) compared to Caucasian American (CA) patients. Pro-inflammatory bacteria such as *F. nucleatum* and *Enterobacter* species were significantly higher in AAs. Also, AA patients have been shown to have decreased microbial diversity compared to CA patients. Some studies have shown that using microbiome profiles in conjunction with certain risk factors such as age, race and body mass index may help predict healthy colon *vs* one with adenomas or carcinomas. Periodontitis is one of the most common bacterial infections in humans and is more prevalent in Non-Hispanic-Blacks as compared to Non-Hispanic Whites. This condition causes increased systemic inflammation, immune dysregulation, gut microbiota dysbiosis and thereby possibly influencing colorectal carcinogenesis. Periodontal-associated bacteria such as *Fusobacterium,* *Prevotella*, *Bacteroides* and *Porphyromonas* have been found in CRC tissues and in feces of CRC patients. Therefore, a deeper understanding of the association between oral and gastrointestinal bacterial profile, in addition to identifying prevalent bacteria in patients with CRC and the differences observed in ethnicity/race, may play a pivotal role in predicting incidence, prognosis, and lead to the development of new treatments.

**Key Words:** Colorectal cancer; Oral microbiome; Gut microbiome; Hallmarks of cancer; Racial/ethnic microbial diversity

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**Core Tip:** In this review, we describe oral and gut microbiome associated with colorectal (CRC) carcinogenesis in relation to the “hallmarks of cancer” and microbial diversity and abundance between races/ethnicities. CRC patients showed increased levels of *Bacteroides, Prevotella, Escherichia coli*,enterotoxigenic *Bacteroides fragilis,Streptococcus gallolyticus,Enterococcus faecalis,Fusobacterium nucleatum* (*F. nucleatum*) and *Clostridium difficile*. Higher levels of *Bacteroides, F. nucleatum* and *Enterobacter* species have been found in African American (AA) compared to Caucasian American (CA) CRC patients. Also, AA patients had decreased microbial diversity compared to CA patients. Periodontal-associated bacteria, *Fusobacterium, Prevotella*, *Bacteroides* and *Porphyromonas*, have been found in CRC tissues and in feces of CRC patients.

**INTRODUCTION**

Colorectal cancer (CRC) is the third most commonly diagnosed cancer and the third leading cause of cancer death[1] with higher incidence and mortality rates for African Americans (AA) among general population[2]. The incidence rates are 24% higher in Non-Hispanic (NH) black males and 19% higher in NH black females, while the death rates are 47% higher in NH black men and 34% higher in NH black women compared to NH white men and women[3]. This significant impact underscores the importance of further understanding the mechanisms and factors that influence the progression of CRC so as to alter the disease process before it has progressed to cancer or improve outcomes in those with a CRC diagnosis. The microbiome and its potential role in colorectal carcinogenesis is a newly emerging yet important field of study.

Current evidence indicates a complex interplay between the gut microbiome, genetic alterations and environmental factors. The gut microbiome is highly diverse and compared to the human genome it contains approximately 100 times the number of genes[4]. There are vast differences found in the microbiota of apparently healthy individuals. Variables such as differences in host genetics, antibiotics usage, environmental and lifestyle factors, including ethnicity, geographic location, and urbanization may modify the gut microbiome[5]. The epithelial surface and mucus layer are enriched with *Clostridium*, *Lactobacillu*s and *Enterococcus* and the intestinal lumen is enriched with *Bacteroides*, *Bifidobacterium, Streptococcus, Enterobacteriaceae, Enterococcus, Clostridium* and *Lactobacillus*[6]. Certain microorganisms could protect against pathogens that promote carcinogenesis by competing for attachment sites and thus preventing the development of CRC[7]. Probiotic strains of *Lactobacillus* and *Bifidobacterium* are thought to play a protective role by competing for adhesion sites, secreting antibacterial peptides and displacing the enteropathogens, *Salmonella typhimurium* and *Escherichia coli* (*E. coli*)*,* as demonstrated in an enterocyte-like Caco-2 cell layer[8]. In CRC patients, a significantly reduced level of *Bifidobacterium* has been found[7]. In contrast, several studies have reported increased levels of *Bacteroides, Prevotella, E. coli,*enterotoxigenic *Bacteroides fragilis* (*B. fragilis*),*Streptococcus gallolyticus* (*S. gallolyticus*)*,Enterococcus faecalis* (*E. faecalis*)*,Fusobacterium nucleatum* (*F. nucleatum*) and *Clostridium difficile* in CRC subjects[9-15]. Additional human studies also have confirmed that *F. nucleatum* is associated with other Gram-negative bacteria, such as *Streptococcus*, *Campylobacter* and *Leptotrichia*, and synergistically promotes CRC[14].

Recent epidemiological studies have examined the association between periodontal diseases and CRC risk. Periodontitis is one of the most common bacterial infections in humans. In periodontitis, pathogenic opportunistic microorganisms in the oral cavity damage the integrity of the tooth-supporting tissues causing increased systemic inflammation, immune dysregulation, gut microbiota dysbiosis and thereby possibly influencing colorectal carcinogenesis[16,17]. *F. nucleatum* is one of the most prevalent species found in extra-oral sites. This bacterium regulates biofilm organization and interacts with the host cells by producing various adhesins and associates with other bacteria through cross-feeding and metabolic interactions[18]. As such, *F. nucleatum* has been suggested to be a "driver bacterium" with pro-carcinogenic characteristics that contribute to tumor development by facilitating "passenger bacteria" to continue the progression of CRC[19]. Periodontal-associated bacteria such as *Fusobacterium*, *Prevotella*, and *Bacteroides* have been found in CRC tissues[9] and *Fusobacterium* and *Porphyromonas* in feces of CRC patients[19,20]. Half of Americans age 30 or older have periodontitis and this increases to 70% for adults aged 65 years and older[7]. Moreover, the prevalence in NH blacks is 59.1% as compared to 40.8% in NH whites[7].

Race/ethnicity also has been associated with variations in microbial abundance. Analysis of the gut microbiota by 16S in 1673 participants in the United States reported 12 microbial genera and families that vary by race/ethnicity. This suggests that the gut microbiota could be inherited and associated with human genetic variation[21]. Farhana *et al*[22] analyzed microbial communities in colonic effluents using 16SRNA profiling from AA and Caucasian American (CA) patients scheduled for an outpatient screening colonoscopy. The results showed higher levels of *Bacteroides* in AAs compared to CAs. Pro-inflammatory bacteria such as *F. nucleatum* and *Enterobacter* species were significantly higher in AAs. Also, AA patients had decreased microbial diversity compared to CA patients[22]. A study conducted in Malaysia reported that *Parvimonas micra*, *F. nucleatum*, *Peptostreptococcus stomatis* and *Akkermansia muciniphila* were enriched in colon tissue of CRC patients[23]. Another study described four periodontal pathogens, *Porphyromonas gingivalis*, *Prevotella intermedia*, *Treponema denticola*, and *Filifactor alocis*, to be more prevalent among AAs than among CAs[24]. Significant differences in oral and gut microbial diversity and abundance between AA and CA may play a role in the CRC disparity observed between the populations.

The “Hallmarks of Cancer,” proposed by Hanahan and Weinburg[25] organize the fundamental processes involved in the complex progression from normal cell to a tumorigenic state within a neoplastic environment. During carcinogenesis, various changes affect the host environment processes such as cellular metabolism and immunological function. Several intestinal microbes may influence the initiation and progression of tumorigenesis by modulating host factors that comprise the hallmarks of cancer[26]. This influence may occur locally and distantly through infection and microbial products, by changing the metabolism of the products produced by host and microbes or by modulating tumor immunosurveillance, which in turn alters the balance between the rate of cell proliferation and apoptosis, triggering chronic inflammation and immunosuppression[27].

Here, we summarize the current knowledge on how specific members of the microbiota and their bacterial machinery influence the hallmarks of cancer in the initiation and progression of CRC (Table 1). Each listed bacterial species is systematically presented according to the following scheme: (1) Tumor-promoting inflammation; (2) Avoiding immune destruction; (3) Deregulating cellular energetics; (4) Sustaining proliferative signaling; (5) Inducing angiogenesis; (6) Resisting cell death; and (7) Genome instability and mutations.

**TUMOR-PROMOTING INFLAMMATION**

A progressive interplay between tissue cells, microbiota and immune cells has been described. T and B cells present in the intestinal mucosa have location-specific phenotypes and functions that can be modified by the microbiota[28]. Commensal microbiota can modulate innate immune cells to release pro-inflammatory cytokines such as interleukin 6 (IL-6), IL-23 and IL-1β, which stimulate the expansion of T-helper-17 (Th17) cells. Th17 cells are a unique CD4+ T-helper subset that secrete the cytokine IL-17. IL-17 increases Paneth cell production of anti-microbial peptides and promotes inflammation by the recruitment of polymorphonuclear neutrophils from the bloodstream[29]. Th17 have pro-tumorigenic effects and it has been associated with worse prognosis in CRC, as shown in Figure 1[30]. While Th17 immune responses promote tumor development, other cytotoxic immune cells, such as natural killer (NK) and CD8+ T cells, are essential for recognizing and eliminating cancer cells[31].

One commonality across many diseases in which microbiota contribute to progression is the disruption of the mucosal/epithelial layers of organs, allowing bacteria and their metabolites to enter compartments that are not normally in close proximity to microbes[32]. This can trigger a local chronic inflammatory response, due to perpetually injured tissues and thus a constant stream of infiltrating microbes/microbial products. Resident commensal bacteria may trigger exaggerated immune responses (colitis) when key components of immune tolerance are broken and/or modify the general immune response upon entering systemic circulation[33-35]. Such disruption may allow some non-native bacterial species to colonize the gut and adapt to the new environment, including oral bacterium. For example, *Fusobacterium*, *Peptostreptococcus,* and *Lactococcus* access and adhere to the basement membrane of the gut in setting of CRA and CRC[9].

*F. nucleatum* is an obligate anaerobic gram-negative bacteria commonly present in the mouth and typically a poor colonizer of healthy and intact intestinal mucosa[9]. Elevated *F. nucleatum* colonization in the normal tissues may predispose to the development of colorectal adenoma (CRA). Its virulence factor FadA adhesion gene (*fadA*) has been found in the colon tissue from patients with CRA and CRC in > 10-100 times higher compared to healthy individuals[36]. Other studies using metagenomic and transcriptomic analyses also have shown an enrichment of *Fusobacterium* species in CRA compared with adjacent normal tissue[7,37-39]. Infections of *Streptococcus galloyticus* (*S. galloyticus*) have been associated with CRC and CRA. *S. galloyticus*, formerly known as *Streptococcus bovis* (*S. bovis*), bacteremia has been associated with colon cancer in 25% to 80% of cases and *S. galloyticus* endocarditis has been associated with colon cancer in 18% to 62% of cases[11,40-45]. *S. galloyticus* has shown a specific association with CRC and CRA when compared with the more dominant intestinal bacteria, *B. fragilis*[46].

Enterotoxigenic *Bacterioides fragilis* (*ETBF*) is an anaerobic gram-negative rod that is known to have an affinity for colonizing the colonic mucosa[47]. Asymptomatic carriage can be seen in up to 40% of healthy children and adult fecal samples[48]. The pathogenicity of *ETBF* is a result of the *B. fragilis* toxin (BFT), which has 3 isotypes (BFT-1, BFT-2, BFT-3). BFT-1 is believed to more commonly colonize stool and BFT-2 more commonly colonizes the mucosa[49]. An association between *ETBF* and CRC is emerging. *ETBF* enhances Th17-driven inflammation and colonic tumor development. *B. fragilis* preferentially colonize the epithelial crypts of the colonic mucosa and thus evade the host immune response leading to a more stable colonization in CRC[10,50]. In general, *ETBF* in CRC patients has been more commonly found on the colonic mucosa as opposed to stool samples[51]. It has been hypothesized that the human colon’s exposure to BFT may lead to a chronic, possibly focal, inflammation of colonic mucosa thus creating sites susceptible to carcinogenesis. BFT induces both acute and chronic colitis and carcinogenesis mediated by IL-17[52]. In multiple intestinal neoplasia (Min) mice, Wu *et al*[53] described a signal transducer and activator of transcription 3 that led to a pro-carcinogenic Th17-dependent pathway for inflammation-induced cancer by *ETBF.*

Some bacterial species, such as *Proteobacteria, E. coli* and *Bacteroides thetaiotamicron*, have evolved to survive amidst harsh conditions of immune activation[54,55]. *E. coli*, which is benign under homeostatic conditions, possesses a significant growth advantage as it utilizes inflammatory nitric oxides as an energy source[54]. In the absence of IgA, the commensal bacterium *Bacteroides thetaiotaomicron* expresses high levels of gene products that are involved in the metabolism of nitric oxide and generates pro-inflammatory signals in the gut[55].

*F. nucleatum* is capable of affecting both innate and adaptive immune responses[7]. *F. nucleatum* enhances inflammation through engagement of its adhesin FadA. The host endothelial receptor for FadA is the vascular endothelial cadherin (CDH5), which is a member of the cadherin family[15]. FadA adheres to and invades epithelial and endothelial cells and activates inflammatory cytokines (IL-6, IL-8, IL-10, IL-18, TNF-α and NF-κB levels) that create a pro-inflammatory environment which accelerates the progression of CRC (Table 1)[15,56,57].

Within the host cytoplasm, *F. nucleatum* may release its RNA, leading to detection by cytosolic retinoic acid-inducible gene I (RIG-I), a cytosolic pattern recognition receptor (PRR) responsible for the type-1 interferon (IFN1) response, thereby stimulating cytosolic NF-kB and promoting inflammation. It generates a pro-inflammatory microenvironment outside the tumor cell through recruitment of tumor-infiltrating immune cells as the primary mechanism[15]. The ability of *F. nucleatum* to invade HEK293T cells, human embryonic kidney cells, which lack endogenous Toll-like receptors, allows the bacteria to activate a pro-inflammatory response through cytosolic pattern recognition receptors, NOD-1, NOD-2 and NF-ĸB signaling. This pro-inflammatory response is mediated by the p38 MAPK signaling pathway[58]. In a mouse model of intestinal cancer, introduction of *F. nucleatum* to ApcMin/+ mice resulted in accelerated small intestinal and colonic tumorigenesis, infiltration of specific myeloid cell subsets into tumors, and an NF-κB proinflammatory signature. This proinflammatory signature is shared with human CRC tissues with a high *Fusobacterium* abundance[39]. Additionally, a positive correlation has been found between the bacterial concentration in human tissues, for adenoma and non-adenoma controls, and TNF-α and IL-10 abundance[59]. Unlike other bacteria associated with CRC, however, *F. nucleatum* does not exacerbate colitis, enteritis, or inflammation-associated intestinal carcinogenesis. This suggests that *F.* *nucleatum* may drive non-colitis-associated intestinal tumorigenesis (Table 1).

*Helicobacter pylori* (*H. pylori*) is a small, spiral, gram-negative bacillus that has a well-established association with the development of gastric cancer and is considered a carcinogen by the World Health Organization[60]. There are conflicting data on the correlation of *H. pylori* as an etiological factor of CRC. The production of oxidative stress involves alteration of the intragastric environment through bacterial and neutrophilic production of ROS, pro-inflammatory cytokines, and upregulation of cyclooxygenase-2 (COX-2)[61]. This includes excessive production of ROS by neutrophils in an effort to eradicate the bacteria. The bacterial infection causes inflammation, leading to increased production and activity of COX-2 and prostaglandin E2, a biomarker associated with inflammation and CRC risk. Some evidence has been reported to support a potential association between *H. pylori* and CRC. Shmuely *et al*[62] described that cag-positive *H. pylori* strains were associated with a 10.6-fold increased risk of CRC compared to cagA negative strains. A systematic review with a meta-analysis found a moderate correlation between *H. pylori* infection and the risk of CRC[63]. Further investigations should be conducted to determine the role of cagA, and the mechanism by which *H. pylori* induces gastric carcinogenesis and potentially CRC.

*S. gallolyticus* produce a similar effect as *H. pylori*. *In vitro* experiments have shown that the binding of *S. gallolyticus* to intestinal cells leads to production of cytokines[36,46,64]. It has been described that treatment with *S. bovis* or wall-extracted antigens in adult rats promoted the progression of preneoplastic lesions through the increased formation of hyperproliferative aberrant colonic crypts, and increased the production of IL-8 in the colonic mucosa[64].

**AVOIDING IMMUNE DESTRUCTION**

*F. nucleatum* directly interacts with the host immune system. Fap2, an autotransporter domain found in the bacterial outer membrane protein, facilitates *F. nucleatum* to adapt to different body habitats. In the oral cavity, Fap2 attaches to neighboring bacteria by co-adhering to different microorganisms, increasing the diversity and the stability of the developing dental biofilm[65]. Fap2 protein adhesion directly interacts with immunoglobulin and immunoreceptor tyrosine-based inhibitory motif domains (TIGIT) expressed in tumor-infiltrating lymphocytes, leading to the inhibition of NK cell cytotoxicity (Figure 2)[31]. TIGIT is an inhibitory receptor present on human NK cells and on various T cells. The interaction between *F. Nucleatum*, Fap2 and TIGIT induces lymphocytes apoptosis and generates an immuno-suppressive microenvironment that promotes the progression of colorectal tumors[15]. Fap2 protein is believed to directly interact with TIGIT, leading to the inhibition of NK cell cytotoxicity[31]. These results identify a bacterium-dependent, tumor-immune evasion mechanism in which tumors exploit the Fap2 protein of *F. nucleatum* to inhibit immune cell activity *via* TIGIT[31]. Several clinical and animal studies have correlated the abundance of *F. nucleatum* with suppression of antitumor T cell response by affecting the enhancement of myeloid-derived suppressor cells and tumor-associated macrophages (Table 1).

Furthermore, various microRNAs are induced during the macrophage inflammatory response and modulate host-cell responses to pathogens. MicroRNA-21 increases the levels of IL-10 and prostaglandin E2, which suppress antitumor T-cell-mediated adaptive immunity through the inhibition of the antigen-presenting capacities of dendritic cells and T-cell proliferation in CRC cells (Figure 2). *F. nucleatum* can expand myeloid-derived immune cells, which inhibits T cell proliferation and activation resulting in tumor cell growth by blocking the middle (G1) phase of the cell cycle and attracting myeloid-derived suppressor cells to the tumor site. *F. nucleatum* also induces T-cell apoptosis in CRC (Table 1)[66].

**DEREGULATING CELLULAR ENERGETICS**

Fermentation of dietary fibers leads to the production of short-chain fatty acids (SCFAs), such as butyrate, which serve as the primary energy source for intestinal cells (Figure 3). The presence of butyrate has an anticancer effect by starving cancer cells. Additionally, it produces epigenetic modifications by inhibiting cell proliferation and promoting apoptosis by inhibiting histone deacetylase[67]. Non-cancerous colonocytes utilize butyrate as their primary energy source in contrast with CRC cells which primarily use glucose and undergo increased glycolysis, a phenomenon known as the Warburg effect or aerobic glycolysis, decreasing mitochondrial oxidative metabolism[55,68].

*Fusobacteria* species also participate in the metabolism of amino acids ingested in the diet, generating formyl-methionyl-leucyl-phenylalanine and SCFAs that chemoattract myeloid cells. This explains the intratumoral expansion of myeloid cells that interconnect tumor, bacterial and immune cells metabolism (Table 1)[39]. In addition, *F. nucleatum* is an asaccharolytic bacterium, a competitive advantage in the tumor milieu; therefore, it will not compete for glucose, a preferred substrate for tumor metabolism[69].

Some bacterial communities could protect intestinal cells from inflammation and tumorigenesis. SCFAs function as signaling molecules between gut epithelia and immune cells modulating changes in the gene expression and providing nutrition to colonocytes. The three major SCFAs produced by bacterial fermentation of carbohydrates are acetate, propionate, and butyrate[70]. Published evidence supports the idea that butyrate is tumor-suppressive by inhibiting the proliferation of CRC cell lines while stimulating their apoptosis and/or differentiation (Figure 3)[40,54,55]. A Western diet slows mucus growth rate and increases penetrability of the colonic mucus barrier, and this effect co-occurs with the shifts in microbial community characterized by gradual decrease of SCFA-producing bacteria, such as *Bifidobacterium* and *Bacteroidales* family and increases in *Firmicutes*[71].

A higher prevalence of *Fusobacterium* and *Porphyromonas* in feces of CRC patients has been reported[19,20]. An increase in glutamate levels by 76% in fecal samples from colon cancer patient samples was reported but there was no increase in glutamine levels. The authors hypothesized that tumor cells may exhibit an increase of glutaminase activity, which results in the conversion of glutamine to glutamate. This supports the theory of the role of certain bacteria as "driver bacteria" with pro-carcinogenic characteristics that contribute to tumor development and then a transition to "passenger bacteria" that contribute to an environment conducive to cancer[19].

Hester *et al*[72] compared bacteria and SCFA in stool samples of AA and CA in a small pilot study. They found lower acetate, butyrate, total SCFA content and a higher pH in AA compared to the other racial groups. Similar results reported in another study where AA had increased levels of SCFAs in stool than other racial/ethnic groups and significantly lower intake of non-starchy vegetables[73]. Wnt/B-catenin signaling plays a fundamental role in several biological processes such as development and cell proliferation related to tumorigenesis. Butyrate has beneficial effects in reducing colon cancer risk with anti-inflammatory, immunomodulatory effects and down regulating Wnt signaling, which inhibits cell proliferation and migration. In addition, AA had higher levels of *Firmicutes* bacteria compared to CA and Hispanics. Moreover, the ratio of *Firmicutes* compared to *Bacteriodes*, which has been associated with obesity, was higher in AA. These results continue to suggest that AA have higher risk of developing colon cancer[72].

**SUSTAINING PROLIFERATIVE SIGNALING**

E-cadherin is a type of cell adhesion molecule and usually is targeted by various intestinal bacteria promoting epithelial proliferation by activating the Wnt/β-catenin pathway. *ETBF*, an enterotoxin-producing bacterium, is involved in the initiation and progression of CRC by not only modulating the mucosal immune response, but also inducing epithelial cell changes. BFT promotes cleavage of E-cadherin (Table 1). This produces nuclear translocation of β-catenin and subsequent transcription of the c-Myc proto-oncogene causing hyperplasia due to proliferation of colonocytes[74]. After treatment of HT29/C1 human colon cancer cells with BFT, cleavage of membrane-associated E-cadherin and loss of intercellular adhesion occurs. This in turn leads to subsequent expression of β-catenin nuclear signaling and induction of c-Myc translation resulting in persistent cell proliferation[75]. The presence of *ETBF* may contribute to chronic colon diseases, including oncogenic transformation, intestinal inflammation, chronic colonic dysfunctions, and colorectal precancerous and cancerous lesions[75].

The mucosa associated/internalized *E. coli* have been shown to occur more frequently in patients with CRC than healthy controls[76-78]. Pathogenic *E. coli* produces virulence factors called cyclomodulins (CM). These CMs can modulate cell cycle progression, apoptosis, cell differentiation, and proliferation (Table 1)[79,80].

Senescent cells secrete growth factors that increases cell proliferation resulting in tumor growth. Colibactin-producing (pks+) *E. coli* promote CRC cancer in a murine AOM/IL-10−/−(azoxymethane/IL) mouse model by expression of SENP1, microRNA-20a-5p, hepatocyte growth factor (HGF) and phosphorylation of HGF receptor. In addition, senescence-associated secretory phenotype induces epithelial cell proliferation *via* the production of growth factors by senescent cells. SENP1 downregulation and p53 SUMOylation are key features of pks+ *E. coli*-induced senescence as result of modifying p53 function[81].

*F. nucleatum* has shown a propensity to adhere to mucosa enabling it to invade human epithelial and endothelial cells[7]. The percentage of *F. nucleatum*-enriched CRC gradually increases from rectum to cecum, suggesting that the rate of bacteria proliferation differs among the intestinal sites[82]. *F. nucleatum* enhances epithelial proliferation through engagement of its adhesin FadA. FadA modulates E-cadherin, a tumor suppressor gene, and activates β-catenin signaling, leading to increased expression of oncogenes, Wnt genes, and inflammatory genes as well as growth stimulation of CRC cells (Figure 4 and Table 1)[56]. The FadA binding site on E-cadherin has been mapped to an 11-amino-acid region. The experimental use of an 11-amino-acid inhibitory synthetic peptide has been shown to inhibit *F. nucleatum* from binding and invading the epithelial cells and abolishing all subsequent host responses, including tumor growth and inflammatory responses (Table 1)[56].

*S. gallolyticus*-induced mucosal inflammation may lead to enhanced mucosal permeability and increased entry for *S. gallolyticus* into colonic cells. *S. gallolyticus* *in vitro* also has shown strong adherence to the proteins of the extracellular matrix, collagen I, collagen II and collagen IV, enabling it to have easy entry into cells and successfully colonize both colonic and vascular tissues[46,83]. *S. gallolyticus* is able to grow in bile and can easily bypass the hepatic reticulo-endothelial system and access the systemic circulation[84]. *S. gallolyticus* endocarditis infections also have been associated with increased hepatic dysfunction[85]. It is hypothesized that underlying colonic disease or *S. gallolyticus*’s effects on the liver’s production of immunoglobulins and bile acids may promote *S. gallolyticus* overgrowth and thus altering the colonic microbiome[85]. Although the mechanism is unclear, *S. gallolyticus* whole bacteria and wall extracted antigens have shown greater propensity towards colonizing colonic tumor cells compared to normal mucosa (Table 1)[36]. *S. gallolyticus* also may induce uncontrolled cell proliferation by triggering proteins known as mitogen activated protein kinases that promote cellular transformation and genetic mutations[36].

**INDUCING ANGIOGENESIS**

*S. gallolyticus* is believed to promote the advancement of preneoplastic lesions to neoplastic lesions through the increased formation of aberrant colonic crypts that show increased expression of cytokines such as IL-8 (Table 1)[64]. IL-8 is a cytokine that stimulates angiogenesis which in turn also may promote carcinogenesis[86]. The pattern of IL-8 mRNA expression in the tumor microenvironment may function as a significant regulatory factor rather than a promoter for the adenoma progression and the adenoma–carcinoma transition. This might be attributed to the angiogenic role of IL-8 by which new blood vessels are formed to meet the increasing demands of cancer growth[46]. Moreover, *S. gallolyticus*-induced overexpression of COX-2 *via* prostaglandins acts as a promoter of carcinogenesis by inducing angiogenesis[36].

**RESISTING CELL DEATH**

*S. gallolyticus* plays an essential role in the oncogenic progression through different factors that cause an anti-apoptotic effect in colorectal mucosa as shown in Figure 5. In Abdulamir *et al*[46], *S. gallolyticus* appeared to induce mRNA expression of proinflammatory cytokines, IL-1 and COX-2 which induce transformation of normal or premalignant colorectal tissues into malignant status. After analysis of mRNA expression of the oncogene c-Myc and antiapoptotic Bcl-2 were not linked to colonization by these bacteria, but were associated with CRC transformation. These results may suggest that *S. gallolyticus* does not induce oncogenic changes or suppress cellular apoptosis, and might instead have a role as a propagator for premalignant or oncogene-positive tissues to enter the transformation cycle through inflammatory and angiogenic microclimates (Table 1)[87]. The release of PGE2-mediated by *S. gallolycticus* is correlated with the overexpression of COX-2, which is seen in about 85% of colon cancers, and through its association with enhanced angiogenesis and inhibition of apoptosis, is favorable to the development and progression of CRC[36]. In addition, this group also found *S. gallolyticus*-seropositive CRC patients were significantly associated with higher mRNA expression of both NF-kB and IL-8 that play an integrated role in a series of steps to escape cell death signals[88].

**GENOME INSTABILITY AND MUTATIONS**

A study comparing microbiota from more than 1000 fecal samples including 416 pairs of twins identified numerous microbial taxa whose abundance was influenced by host genetics. In the case of monozygotic twins, a more similar microbiota was observed than in dizygotic twins. However, it is unclear whether the host's genetic variation shapes and interacts with the gut microbiome to affect the host's phenotype[89]. The analysis of gut microbiota in stool of 2084 participants in the Healthy Living in an Urban Environment Study described that people who live in the same city tend to show similar gut microbiota with other people of their ethnic origin[90]. Ethnic differences in alpha diversity and inter-individual differences were independent of metabolic health and were only partially explained by ethnic characteristics, including sociodemographic, lifestyle, or dietary factors. Therefore, the ethnicity of individuals may be an important factor to consider in the research of microbiome and cancer CRC[90].

Sulfidogenic bacteria, such as *Fusobacterium*, *Desulfovibrio* and *Bilophila wadsworthia*, have been implicated in CRC development through the production of hydrogen sulfide (Figure 6)[91]. Hydrogen sulfide is a genotoxic compound that has been shown to damage DNA leading to genomic or chromosomal instability (CIN), effecting DNA repair in a multistep carcinogenic process. One hypothesis is that hydrogen sulfide diffuses into intestinal epithelial cells and interferes with mitochondrial function, ultimately leading to hyperproliferation *via* the Ras/MAPK pathway[92]. The hyperactivation of the Ras/MAPK pathway is a known mechanism of carcinogenesis in CRC. A study described the concentration of specific bacterial DNA in colonic tissue biopsies, and showed that AA with CRC had higher concentrations of sulfidogenic bacteria compared to NH whites. At the same time, AA with CRC had increased levels of sulfidogenic bacteria compared to AA without CRC[93].

Some bacterial products, such as colibactin or BFT, may damage the genetic information inside the nucleus, and actively induce DNA damage in organs that are in direct contact with the microbiome (Figure 6 and Table 1)[94]. These genotoxins may directly promote the release from macrophages and other inflammatory cells of reactive oxygen species (ROS), reactive nitrogen species (RNS) and hydrogen sulfide (H2S) from the bacterial microbiota products[95]. ROS and RNS inhibit the activity of T cells, including antitumor cytolytic CD8+ T cells. An abundance of myeloid-derived suppressor cells also leads to increased production of ROS and RNS and subsequent tumor-supporting inflammation and neoangiogenesis[70]. Hydrogen sulfide has been shown to damage DNA leading to genomic or CIN, affecting DNA repair in a multistep carcinogenic process. One hypothesis is that hydrogen sulfide diffuses into intestinal epithelial cells and interferes with mitochondrial function, ultimately leading to hyperproliferation *via* the Ras/MAPK pathway[92]. Furthermore, metabolic actions of the microbiome may promote the development of CRC by activation of other genotoxins such as acetaldehyde, dietary nitrosamine and other carcinogens[95].

As shown in Figure 6, various gut microbes and their bacterial products can cause DNA mutations. *E. coli* contribute to the accumulation of mutations resulting from DNA damage induced by genotoxins, or by downregulating host DNA mismatch repair proteins (Table 1)[96]. One cyclomodulin is a hybrid polyketidenonribosomal peptide called colibactin, encoded by the polyketide synthase (pks) genomic island. Colibactin possesses genotoxic properties that result in CIN and double-strand breaks in the DNA of human eukaryotic cells. *E. coli* strains harboring the pks genotoxic island, which are found in a significantly high percentage of inflammatory bowel disease and CRC patients[79]. *In vitro* studies using different mammalian cells, including normal intestinal cells, showed that pks+ *E. coli* produce DNA double-strand breaks affecting the normal cellular division with the consequent cell cycle arrest and aneuploidy[97]. Conversely, different commensal bacteria could harm DNA strands by stimulating host inflammation and producing a pro-oxidant microenvironment. *ETBF* causes DNA damage by peroxide that comes from the colonocyte expression of enzyme spermine oxidase[98].

*E. faecalis* may have a microbiome driven bystander effect that leads to increased COX-2 expression in macrophages leading to ROS formation, which in turn promotes CIN in intestinal epithelial cells. Primary colonic epithelial cells can have induction of CIN or malignant tumor aneuploidy *via* macrophages that have been polarized by *E. faecalis*[99]. These results validate a novel mechanism for CRC that involves endogenous CIN and cellular transformation arising through a microbiome-driven bystander effect (Figure 6)[100].

*Enterococci* have increasingly been shown to cause infections in the elderly. They are gram positive, facultative anaerobe, diplococci that grow as short chains. *E. faecalis* has been found to aggregate at higher levels in stool samples in CRC patients than in healthier controls[101,102]. It also has been shown to be in greater abundance in the adjacent tissues of CRC when compared to healthy mucosa in controls[103]. It has been postulated that *E. faecalis* can damage colonic DNA and cause genomic instability *via* its ability to generate ROS that predisposes to mutations leading to CIN and subsequent carcinogenesis (Figure 6)[12].

A large abundance of *F. nucleatum* has been shown to induce a series of tumor-specific molecular events, including the CpG island methylating phenotype (CIMP), microsatellite instability (MSI), and genetic mutations in BRAF, CHD7, CHD8 and TP53. A higher abundance of *F. nucleatum* DNA in CRC tissues has been associated with an increased CRC-specific mortality, evidence that suggests *F. nucleatum* may potentially serve as a prognostic biomarker (Figure 6)[82].

Several etiological mechanisms of *H. pylori* in CRC pathology have been hypothesized. One alternative is that chronic *H. pylori* infection can lead to hypergastrinemia, which is considered to be a nutrient factor in the colorectal mucosa and may lead to the promotion of mutagenesis. In addition, this bacterial infection and bacterial CagA protein lead to chronic gastritis with an increase in gastrin production (Figure 6)[62]. Ammonia produced by *H. pylori* might also act as an endogenous carcinogen. More studies are needed to investigate the potential role of gastrin in the mechanisms of metastasis of the tumor cells[63].

**CONCLUSION**

In this review, we highlight the various gut and oral microbiota associated with CRC and CRA, and their proposed molecular mechanisms in relation to the processes of “the hallmarks of cancer.” Common oncogenic mechanisms include disruption of mucosal/epithelial layer of organs, promotion of inflammation and neoangiogenesis, use of genotoxins by bacteria, altering of genetic expression, and modification or weakening of the existing immune system.

To understand whether host genetics play a role in the associations between race/ethnicity, and oral and gut microbiota, it is essential to perform genome-wide association studies with microbial data among diverse populations. In 2016, 81% of existing genome-wide association study data was generated from individuals of European descent where the proportion of samples from individuals of African descent only increased by 2.5% and that of ancestry Hispanic or Latin American by about 0.5%[104]. There are huge gaps in knowledge related to understanding the underlying causes of racial/ethnic differences in the gastrointestinal microbiota and their possible role in colon cancer. Therefore, it is essential to be able to generate new knowledge by generating large and representative cross-sectional studies with gut, oral and fecal samples in populations that include individuals with various social determinants of health (for example, NHANES). Variables that could cause these racial/ethnic differences, such as diet, habits, socioeconomic status and oral health status should also be further studied. Genetic factors may contribute to biological reasons for CRC disparity. Diverse studies described somatic alterations in well-known CRC genes (APC, BRAF, KRAS, and PIK3CA) and lower frequency of MSI, a good prognostic biomarker, among AA patients[105,106]. *F. nucleatum* levels have been found to be significantly higher in AAs[22] and has been shown to induce a series of tumor-specific molecular events, including CIMP, MSI, and genetic mutations in oncogenes and tumor suppressors[82].

Differences in the immunological profiles of colon tumors from AA compared to CA suggested a deficiency of appropriate immune defense mechanisms in terms of gene expression, recruitment of immune cells and systemic secretion of cytokines. As such, these immune differences could be mitigated through population-specific therapeutic approaches[106]. Studies of associations between specific taxa in microbiome and race/ethnicity could provide an insight for examining specific bacterial members as mediators of health disparities. Defining the composition of a “healthy microbiota” is one of the challenges in the field of microbiome research. Our review reveals that unique opportunities exist in targeting racial/ethnic differences in oral and gut microbiome for a greater understanding of the complexity of CRC and CRA etiology and carcinogenesis.

As knowledge is gained regarding the microbiome as it pertains to CRC, the clinical implications will continue to grow and hopefully come to the forefront in the prevention, detection, and treatment of CRC in clinical practice. Current non-invasive screening methods for CRC include FIT and Cologuard. However, their ability to detect precancerous lesions is not entirely reliable, thus creating a void for superior noninvasive screening methods that microbiome studies could likely one day fill[107]. When combining testing for oral bacteria *F. nucleatum* with FIT, the combination showed superior sensitivity than FIT alone in detecting CRC, and additionally increased the performance of adenoma detection, suggesting the potential of bacterial biomarkers as more useful diagnostic tools over current diagnostic strategies[108]. In addition, the ratio *F. nucleatum/Bifidobacterium* showed superior sensitivity of 84.6% and specificity of 92.3% for diagnosing CRC in comparison with the use of a single fecal bacterial biomarker candidate[109].

The deficit in the number of butyrate-producing bacteria can have detrimental consequences in the progression of the disease, hence the screening of SCFA and microbial-derived metabolites have potential as biomarkers and diagnostic tools for CRC. Some studies already have shown that using microbiome profiles in conjunction with certain risk factors such as age, race and body mass index can help predict healthy colon *vs* one with adenomas or carcinomas[110]. While detection of CRC and precancerous lesions is our current goal in preventing CRC mortality, the microbiome also provides promise into potentially preventing CRC by inhibiting colorectal tumorigenesis. A recent study by Li *et al*[111] aimed to look at the role of depleted bacteria, specifically *Streptococcus thermophilus* (*S. thermophilus*), in CRC to see if when used as a probiotic that it could prevent CRC. They showed in a mouse model that tumor formation could be reduced using *S. thermophilus* by oral gavage, and it was specifically the β-Galactosidase secreted by *S. thermophilus* that was critical to retarding the growth of CRC cells. *S. thermophilus* also was able to increase other known probiotics, including Bifidobacterium and Lactobacillus, *via* β-Galactosidase. Albeit, just in a mouse model, it highlights the potential for possible prevention and reversal of CRC by use of the microbiome.

Additional prospective human studies must be undertaken to determine the role of the microbiome in CRC therapy and in the reliability of certain profiles for screening and prevention. Furthermore, when certain microbiome signatures that predispose risk for CRC do arise, the age at which one is to start looking for these predispositions also needs to be established to enable clinical use. The heterogeneity of CRC could be related to different microbiota communities that either predispose or provide resistance to the disease, and the profile analysis of the oral microbiome may offer an alternative screen as a biomarker for detecting CRC[112]. Only single studies detected associations with *Fusobacterium*or *Porphyromonadaceae* and CRC[110,113]. Further studies with a larger sample size are needed to confirm the identified associations and estimate the potential utilization of the oral microbiota and periodontal diagnosis and treatment for use in CRC early detection or prevention.

The gut microbiome and its metabolites have therapeutic implications for CRC and other cancers. It has been postulated that therapeutic response to immune checkpoint inhibitors (ICI) may be influenced by presence of the gut microbiome. In 100 patients diagnosed with non- small cell lung cancer and on ICI therapy, the stool of patients responding to ICI therapy was rich in *Akkermansia mucinphilia* compared to nonresponders[114]. The baseline microbiome or its modulation using antibiotics, probiotics or FMT have influenced treatment efficacy in numerous cancers[115]. For example, patients with non-small cell lung cancer, renal cell carcinoma or urothelial cancer treated with antibiotics for routine indications shortly before, during, or shortly after treatment with anti-PD1/PD-L1 mAB had significantly lower progression-free survival and overall survival rates compared to patients who had not received antibiotics. This suggests that disrupting the gut microbiota (*via* antibiotic use) could potentially impair anti-tumor immune responses as well as response to immune checkpoint blockade[114,115].

The gut microbiome is a dynamic meditator of immune and cellular response to cancer and influences the efficacy of cancer therapies. Manipulating the gut microbiome will likely emerge as a viable option of modulating the responsiveness of cancers to immune mediated and other therapies. In addition, other decisions regarding the use of antibiotics with cancer and other therapies should be weighed carefully considering their impact on the gut microbiome. Large prospective studies on the impact of dietary interventions (prebiotics), antibiotic use and the influence of environmental pollutants are needed to clarify many unanswered questions on the factors that impact the gut microbiome and the durability of that effect. Lastly, the price and availability of microbiome analysis will have to come to a point where it is widely available and accessible to make it mainstay in the clinical realm.

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**REFERENCES**

1 **Bray F**, Ferlay J, Soerjomataram I, Siegel RL, Torre LA, Jemal A. Global cancer statistics 2018: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries. *CA Cancer J Clin* 2018; **68**: 394-424 [PMID: 30207593 DOI: 10.3322/caac.21492]

2 **DeSantis CE**, Miller KD, Goding Sauer A, Jemal A, Siegel RL. Cancer statistics for African Americans, 2019. *CA Cancer J Clin* 2019; **69**: 211-233 [PMID: 30762872 DOI: 10.3322/caac.21555]

3 **American Cancer Society**. Colorectal Cancer Facts & Figures 2020-2022. Atlanta: American Cancer Society, 2020

4 **Bäckhed F**, Ley RE, Sonnenburg JL, Peterson DA, Gordon JI. Host-bacterial mutualism in the human intestine. *Science* 2005; **307**: 1915-1920 [PMID: 15790844 DOI: 10.1126/science.1104816]

5 **Stott KJ**, Phillips B, Parry L, May S. Recent advancements in the exploitation of the gut microbiome in the diagnosis and treatment of colorectal cancer. *Biosci Rep* 2021; **41** [PMID: 34236075 DOI: 10.1042/BSR20204113]

6 **Sekirov I**, Russell SL, Antunes LC, Finlay BB. Gut microbiota in health and disease. *Physiol Rev* 2010; **90**: 859-904 [PMID: 20664075 DOI: 10.1152/physrev.00045.2009]

7 **Chen W**, Liu F, Ling Z, Tong X, Xiang C. Human intestinal lumen and mucosa-associated microbiota in patients with colorectal cancer. *PLoS One* 2012; **7**: e39743 [PMID: 22761885 DOI: 10.1371/journal.pone.0039743]

8 **Candela M**, Perna F, Carnevali P, Vitali B, Ciati R, Gionchetti P, Rizzello F, Campieri M, Brigidi P. Interaction of probiotic Lactobacillus and Bifidobacterium strains with human intestinal epithelial cells: adhesion properties, competition against enteropathogens and modulation of IL-8 production. *Int J Food Microbiol* 2008; **125**: 286-292 [PMID: 18524406 DOI: 10.1016/j.ijfoodmicro.2008.04.012]

9 **Gao Z**, Guo B, Gao R, Zhu Q, Qin H. Microbiota disbiosis is associated with colorectal cancer. *Front Microbiol* 2015; **6**: 20 [PMID: 25699023 DOI: 10.3389/fmicb.2015.00020]

10 **Boleij A**, Hechenbleikner EM, Goodwin AC, Badani R, Stein EM, Lazarev MG, Ellis B, Carroll KC, Albesiano E, Wick EC, Platz EA, Pardoll DM, Sears CL. The Bacteroides fragilis toxin gene is prevalent in the colon mucosa of colorectal cancer patients. *Clin Infect Dis* 2015; **60**: 208-215 [PMID: 25305284 DOI: 10.1093/cid/ciu787]

11 **Kok H**, Jureen R, Soon CY, Tey BH. Colon cancer presenting as Streptococcus gallolyticus infective endocarditis. *Singapore Med J* 2007; **48**: e43-e45 [PMID: 17304377]

12 **Huycke MM**, Abrams V, Moore DR. Enterococcus faecalis produces extracellular superoxide and hydrogen peroxide that damages colonic epithelial cell DNA. *Carcinogenesis* 2002; **23**: 529-536 [PMID: 11895869 DOI: 10.1093/carcin/23.3.529]

13 **Ruoff KL**, de la Maza L, Murtagh MJ, Spargo JD, Ferraro MJ. Species identities of enterococci isolated from clinical specimens. *J Clin Microbiol* 1990; **28**: 435-437 [PMID: 2108992 DOI: 10.1128/jcm.28.3.435-437.1990]

14 **Warren RL**, Freeman DJ, Pleasance S, Watson P, Moore RA, Cochrane K, Allen-Vercoe E, Holt RA. Co-occurrence of anaerobic bacteria in colorectal carcinomas. *Microbiome* 2013; **1**: 16 [PMID: 24450771 DOI: 10.1186/2049-2618-1-16]

15 **Shang FM**, Liu HL. *Fusobacterium nucleatum* and colorectal cancer: A review. *World J Gastrointest Oncol* 2018; **10**: 71-81 [PMID: 29564037 DOI: 10.4251/wjgo.v10.i3.71]

16 **Pihlstrom BL**, Michalowicz BS, Johnson NW. Periodontal diseases. *Lancet* 2005; **366**: 1809-1820 [PMID: 16298220 DOI: 10.1016/S0140-6736(05)67728-8]

17 **Han YW**. Fusobacterium nucleatum: a commensal-turned pathogen. *Curr Opin Microbiol* 2015; **23**: 141-147 [PMID: 25576662 DOI: 10.1016/j.mib.2014.11.013]

18 **Brennan CA**, Garrett WS. Fusobacterium nucleatum - symbiont, opportunist and oncobacterium. *Nat Rev Microbiol* 2019; **17**: 156-166 [PMID: 30546113 DOI: 10.1038/s41579-018-0129-6]

19 **Weir TL**, Manter DK, Sheflin AM, Barnett BA, Heuberger AL, Ryan EP. Stool microbiome and metabolome differences between colorectal cancer patients and healthy adults. *PLoS One* 2013; **8**: e70803 [PMID: 23940645 DOI: 10.1371/journal.pone.0070803]

20 **Ahn J**, Sinha R, Pei Z, Dominianni C, Wu J, Shi J, Goedert JJ, Hayes RB, Yang L. Human gut microbiome and risk for colorectal cancer. *J Natl Cancer Inst* 2013; **105**: 1907-1911 [PMID: 24316595 DOI: 10.1093/jnci/djt300]

21 **Brooks AW**, Priya S, Blekhman R, Bordenstein SR. Gut microbiota diversity across ethnicities in the United States. *PLoS Biol* 2018; **16**: e2006842 [PMID: 30513082 DOI: 10.1371/journal.pbio.2006842]

22 **Farhana L**, Antaki F, Murshed F, Mahmud H, Judd SL, Nangia-Makker P, Levi E, Yu Y, Majumdar AP. Gut microbiome profiling and colorectal cancer in African Americans and Caucasian Americans. *World J Gastrointest Pathophysiol* 2018; **9**: 47-58 [PMID: 30283710 DOI: 10.4291/wjgp.v9.i2.47]

23 **Osman MA**, Neoh HM, Ab Mutalib NS, Chin SF, Mazlan L, Raja Ali RA, Zakaria AD, Ngiu CS, Ang MY, Jamal R. Parvimonas micra, Peptostreptococcus stomatis, Fusobacterium nucleatum and Akkermansia muciniphila as a four-bacteria biomarker panel of colorectal cancer. *Sci Rep* 2021; **11**: 2925 [PMID: 33536501 DOI: 10.1038/s41598-021-82465-0]

24 **Yang Y**, Zheng W, Cai Q, Shrubsole MJ, Pei Z, Brucker R, Steinwandel M, Bordenstein SR, Li Z, Blot WJ, Shu XO, Long J. Racial Differences in the Oral Microbiome: Data from Low-Income Populations of African Ancestry and European Ancestry. *mSystems* 2019; **4** [PMID: 31771977 DOI: 10.1128/mSystems.00639-19]

25 **Hanahan D**, Weinberg RA. Hallmarks of cancer: the next generation. *Cell* 2011; **144**: 646-674 [PMID: 21376230 DOI: 10.1016/j.cell.2011.02.013]

26 **Fulbright LE**, Ellermann M, Arthur JC. The microbiome and the hallmarks of cancer. *PLoS Pathog* 2017; **13**: e1006480 [PMID: 28934351 DOI: 10.1371/journal.ppat.1006480]

27 **Dutta D**, Lim SH. Bidirectional interaction between intestinal microbiome and cancer: opportunities for therapeutic interventions. *Biomark Res* 2020; **8**: 31 [PMID: 32817793 DOI: 10.1186/s40364-020-00211-6]

28 **Honda K**, Littman DR. The microbiota in adaptive immune homeostasis and disease. *Nature* 2016; **535**: 75-84 [PMID: 27383982 DOI: 10.1038/nature18848]

29 **Hirota K**, Duarte JH, Veldhoen M, Hornsby E, Li Y, Cua DJ, Ahlfors H, Wilhelm C, Tolaini M, Menzel U, Garefalaki A, Potocnik AJ, Stockinger B. Fate mapping of IL-17-producing T cells in inflammatory responses. *Nat Immunol* 2011; **12**: 255-263 [PMID: 21278737 DOI: 10.1038/ni.1993]

30 **Grivennikov SI**, Wang K, Mucida D, Stewart CA, Schnabl B, Jauch D, Taniguchi K, Yu GY, Osterreicher CH, Hung KE, Datz C, Feng Y, Fearon ER, Oukka M, Tessarollo L, Coppola V, Yarovinsky F, Cheroutre H, Eckmann L, Trinchieri G, Karin M. Adenoma-linked barrier defects and microbial products drive IL-23/IL-17-mediated tumour growth. *Nature* 2012; **491**: 254-258 [PMID: 23034650 DOI: 10.1038/nature11465]

31 **Gur C**, Ibrahim Y, Isaacson B, Yamin R, Abed J, Gamliel M, Enk J, Bar-On Y, Stanietsky-Kaynan N, Coppenhagen-Glazer S, Shussman N, Almogy G, Cuapio A, Hofer E, Mevorach D, Tabib A, Ortenberg R, Markel G, Miklić K, Jonjic S, Brennan CA, Garrett WS, Bachrach G, Mandelboim O. Binding of the Fap2 protein of Fusobacterium nucleatum to human inhibitory receptor TIGIT protects tumors from immune cell attack. *Immunity* 2015; **42**: 344-355 [PMID: 25680274 DOI: 10.1016/j.immuni.2015.01.010]

32 **Belkaid Y**, Hand TW. Role of the microbiota in immunity and inflammation. *Cell* 2014; **157**: 121-141 [PMID: 24679531 DOI: 10.1016/j.cell.2014.03.011]

33 **Berg DJ**, Davidson N, Kühn R, Müller W, Menon S, Holland G, Thompson-Snipes L, Leach MW, Rennick D. Enterocolitis and colon cancer in interleukin-10-deficient mice are associated with aberrant cytokine production and CD4(+) TH1-like responses. *J Clin Invest* 1996; **98**: 1010-1020 [PMID: 8770874 DOI: 10.1172/JCI118861]

34 **Takeda K**, Clausen BE, Kaisho T, Tsujimura T, Terada N, Förster I, Akira S. Enhanced Th1 activity and development of chronic enterocolitis in mice devoid of Stat3 in macrophages and neutrophils. *Immunity* 1999; **10**: 39-49 [PMID: 10023769 DOI: 10.1016/s1074-7613(00)80005-9]

35 **Gopalakrishnan V**, Helmink BA, Spencer CN, Reuben A, Wargo JA. The Influence of the Gut Microbiome on Cancer, Immunity, and Cancer Immunotherapy. *Cancer Cell* 2018; **33**: 570-580 [PMID: 29634945 DOI: 10.1016/j.ccell.2018.03.015]

36 **Biarc J**, Nguyen IS, Pini A, Gossé F, Richert S, Thiersé D, Van Dorsselaer A, Leize-Wagner E, Raul F, Klein JP, Schöller-Guinard M. Carcinogenic properties of proteins with pro-inflammatory activity from Streptococcus infantarius (formerly S.bovis). *Carcinogenesis* 2004; **25**: 1477-1484 [PMID: 14742316 DOI: 10.1093/carcin/bgh091]

37 **Castellarin M**, Warren RL, Freeman JD, Dreolini L, Krzywinski M, Strauss J, Barnes R, Watson P, Allen-Vercoe E, Moore RA, Holt RA. Fusobacterium nucleatum infection is prevalent in human colorectal carcinoma. *Genome Res* 2012; **22**: 299-306 [PMID: 22009989 DOI: 10.1101/gr.126516.111]

38 **Ito M**, Kanno S, Nosho K, Sukawa Y, Mitsuhashi K, Kurihara H, Igarashi H, Takahashi T, Tachibana M, Takahashi H, Yoshii S, Takenouchi T, Hasegawa T, Okita K, Hirata K, Maruyama R, Suzuki H, Imai K, Yamamoto H, Shinomura Y. Association of Fusobacterium nucleatum with clinical and molecular features in colorectal serrated pathway. *Int J Cancer* 2015; **137**: 1258-1268 [PMID: 25703934 DOI: 10.1002/ijc.29488]

39 **Kostic AD**, Chun E, Robertson L, Glickman JN, Gallini CA, Michaud M, Clancy TE, Chung DC, Lochhead P, Hold GL, El-Omar EM, Brenner D, Fuchs CS, Meyerson M, Garrett WS. Fusobacterium nucleatum potentiates intestinal tumorigenesis and modulates the tumor-immune microenvironment. *Cell Host Microbe* 2013; **14**: 207-215 [PMID: 23954159 DOI: 10.1016/j.chom.2013.07.007]

40 **Wilson WR**, Thompson RL, Wilkowske CJ, Washington JA 2nd, Giuliani ER, Geraci JE. Short-term therapy for streptococcal infective endocarditis. Combined intramuscular administration of penicillin and streptomycin. *JAMA* 1981; **245**: 360-363 [PMID: 7452862 DOI: 10.1001/jama.1981.03310290028017]

41 **Reynolds JG**, Silva E, McCormack WM. Association of Streptococcus bovis bacteremia with bowel disease. *J Clin Microbiol* 1983; **17**: 696-697 [PMID: 6853693 DOI: 10.1128/jcm.17.4.696-697.1983]

42 **Leport C**, Bure A, Leport J, Vilde JL. Incidence of colonic lesions in Streptococcus bovis and enterococcal endocarditis. *Lancet* 1987; **1**: 748 [PMID: 2882164 DOI: 10.1016/s0140-6736(87)90391-6]

43 **Zarkin BA**, Lillemoe KD, Cameron JL, Effron PN, Magnuson TH, Pitt HA. The triad of Streptococcus bovis bacteremia, colonic pathology, and liver disease. *Ann Surg* 1990; **211**: 786-91; discussion 791-2 [PMID: 2357141 DOI: 10.1097/00000658-199006000-00019]

44 **Malkin J**, Kimmitt PT, Ou HY, Bhasker PS, Khare M, Deng Z, Stephenson I, Sosnowski AW, Perera N, Rajakumar K. Identification of Streptococcus gallolyticus subsp. macedonicus as the etiological agent in a case of culture-negative multivalve infective endocarditis by 16S rDNA PCR analysis of resected valvular tissue. *J Heart Valve Dis* 2008; **17**: 589-592 [PMID: 18980096 DOI: 10.1016/j.jccase.2011.01.007]

45 **Gupta A**, Madani R, Mukhtar H. Streptococcus bovis endocarditis, a silent sign for colonic tumour. *Colorectal Dis* 2010; **12**: 164-171 [PMID: 19226366 DOI: 10.1111/j.1463-1318.2009.01814.x]

46 **Abdulamir AS**, Hafidh RR, Abu Bakar F. The association of Streptococcus bovis/gallolyticus with colorectal tumors: the nature and the underlying mechanisms of its etiological role. *J Exp Clin Cancer Res* 2011; **30**: 11 [PMID: 21247505 DOI: 10.1186/1756-9966-30-11]

47 **Huang JY**, Lee SM, Mazmanian SK. The human commensal Bacteroides fragilis binds intestinal mucin. *Anaerobe* 2011; **17**: 137-141 [PMID: 21664470 DOI: 10.1016/j.anaerobe.2011.05.017]

48 **Zitomersky NL**, Coyne MJ, Comstock LE. Longitudinal analysis of the prevalence, maintenance, and IgA response to species of the order Bacteroidales in the human gut. *Infect Immun* 2011; **79**: 2012-2020 [PMID: 21402766 DOI: 10.1128/IAI.01348-10]

49 **Franco AA**, Mundy LM, Trucksis M, Wu S, Kaper JB, Sears CL. Cloning and characterization of the Bacteroides fragilis metalloprotease toxin gene. *Infect Immun* 1997; **65**: 1007-1013 [PMID: 9038310 DOI: 10.1128/IAI.65.3.1007-1013.1997]

50 **Lee SM**, Donaldson GP, Mikulski Z, Boyajian S, Ley K, Mazmanian SK. Bacterial colonization factors control specificity and stability of the gut microbiota. *Nature* 2013; **501**: 426-429 [PMID: 23955152 DOI: 10.1038/nature12447]

51 **Haghi F**, Goli E, Mirzaei B, Zeighami H. The association between fecal enterotoxigenic B. fragilis with colorectal cancer. *BMC Cancer* 2019; **19**: 879 [PMID: 31488085 DOI: 10.1186/s12885-019-6115-1]

52 **Myers LL**, Shoop DS, Stackhouse LL, Newman FS, Flaherty RJ, Letson GW, Sack RB. Isolation of enterotoxigenic Bacteroides fragilis from humans with diarrhea. *J Clin Microbiol* 1987; **25**: 2330-2333 [PMID: 3429625 DOI: 10.1128/jcm.25.12.2330-2333.1987]

53 **Wu S**, Rhee KJ, Albesiano E, Rabizadeh S, Wu X, Yen HR, Huso DL, Brancati FL, Wick E, McAllister F, Housseau F, Pardoll DM, Sears CL. A human colonic commensal promotes colon tumorigenesis via activation of T helper type 17 T cell responses. *Nat Med* 2009; **15**: 1016-1022 [PMID: 19701202 DOI: 10.1038/nm.2015]

54 **Winter SE**, Winter MG, Xavier MN, Thiennimitr P, Poon V, Keestra AM, Laughlin RC, Gomez G, Wu J, Lawhon SD, Popova IE, Parikh SJ, Adams LG, Tsolis RM, Stewart VJ, Bäumler AJ. Host-derived nitrate boosts growth of E. coli in the inflamed gut. *Science* 2013; **339**: 708-711 [PMID: 23393266 DOI: 10.1126/science.1232467]

55 **Peterson DA**, McNulty NP, Guruge JL, Gordon JI. IgA response to symbiotic bacteria as a mediator of gut homeostasis. *Cell Host Microbe* 2007; **2**: 328-339 [PMID: 18005754 DOI: 10.1016/j.chom.2007.09.013]

56 **Rubinstein MR**, Wang X, Liu W, Hao Y, Cai G, Han YW. Fusobacterium nucleatum promotes colorectal carcinogenesis by modulating E-cadherin/β-catenin signaling via its FadA adhesin. *Cell Host Microbe* 2013; **14**: 195-206 [PMID: 23954158 DOI: 10.1016/j.chom.2013.07.012]

57 **Yang Y**, Weng W, Peng J, Hong L, Yang L, Toiyama Y, Gao R, Liu M, Yin M, Pan C, Li H, Guo B, Zhu Q, Wei Q, Moyer MP, Wang P, Cai S, Goel A, Qin H, Ma Y. Fusobacterium nucleatum Increases Proliferation of Colorectal Cancer Cells and Tumor Development in Mice by Activating Toll-Like Receptor 4 Signaling to Nuclear Factor-κB, and Up-regulating Expression of MicroRNA-21. *Gastroenterology* 2017; **152**: 851-866.e24 [PMID: 27876571 DOI: 10.1053/j.gastro.2016.11.018]

58 **Quah SY**, Bergenholtz G, Tan KS. Fusobacterium nucleatum induces cytokine production through Toll-like-receptor-independent mechanism. *Int Endod J* 2014; **47**: 550-559 [PMID: 24102075 DOI: 10.1111/iej.12185]

59 **McCoy AN**, Araújo-Pérez F, Azcárate-Peril A, Yeh JJ, Sandler RS, Keku TO. Fusobacterium is associated with colorectal adenomas. *PLoS One* 2013; **8**: e53653 [PMID: 23335968 DOI: 10.1371/journal.pone.0053653]

60 **Handa O**, Naito Y, Yoshikawa T. Helicobacter pylori: a ROS-inducing bacterial species in the stomach. *Inflamm Res* 2010; **59**: 997-1003 [PMID: 20820854 DOI: 10.1007/s00011-010-0245-x]

61 **Lochhead P**, El-Omar EM. Helicobacter pylori infection and gastric cancer. *Best Pract Res Clin Gastroenterol* 2007; **21**: 281-297 [PMID: 17382277 DOI: 10.1016/j.bpg.2007.02.002]

62 **Shmuely H**, Passaro D, Figer A, Niv Y, Pitlik S, Samra Z, Koren R, Yahav J. Relationship between Helicobacter pylori CagA status and colorectal cancer. *Am J Gastroenterol* 2001; **96**: 3406-3410 [PMID: 11774957 DOI: 10.1111/j.1572-0241.2001.05342.x]

63 **Zuo Y**, Jing Z, Bie M, Xu C, Hao X, Wang B. Association between Helicobacter pylori infection and the risk of colorectal cancer: A systematic review and meta-analysis. *Medicine (Baltimore)* 2020; **99**: e21832 [PMID: 32925719 DOI: 10.1097/MD.0000000000021832]

64 **Ellmerich S**, Djouder N, Schöller M, Klein JP. Production of cytokines by monocytes, epithelial and endothelial cells activated by Streptococcus bovis. *Cytokine* 2000; **12**: 26-31 [PMID: 10623439 DOI: 10.1006/cyto.1999.0521]

65 **Coppenhagen-Glazer S**, Sol A, Abed J, Naor R, Zhang X, Han YW, Bachrach G. Fap2 of Fusobacterium nucleatum is a galactose-inhibitable adhesin involved in coaggregation, cell adhesion, and preterm birth. *Infect Immun* 2015; **83**: 1104-1113 [PMID: 25561710 DOI: 10.1128/IAI.02838-14]

66 **Nosho K**, Sukawa Y, Adachi Y, Ito M, Mitsuhashi K, Kurihara H, Kanno S, Yamamoto I, Ishigami K, Igarashi H, Maruyama R, Imai K, Yamamoto H, Shinomura Y. Association of Fusobacterium nucleatum with immunity and molecular alterations in colorectal cancer. *World J Gastroenterol* 2016; **22**: 557-566 [PMID: 26811607 DOI: 10.3748/wjg.v22.i2.557]

67 **Donohoe DR**, Holley D, Collins LB, Montgomery SA, Whitmore AC, Hillhouse A, Curry KP, Renner SW, Greenwalt A, Ryan EP, Godfrey V, Heise MT, Threadgill DS, Han A, Swenberg JA, Threadgill DW, Bultman SJ. A gnotobiotic mouse model demonstrates that dietary fiber protects against colorectal tumorigenesis in a microbiota- and butyrate-dependent manner. *Cancer Discov* 2014; **4**: 1387-1397 [PMID: 25266735 DOI: 10.1158/2159-8290.CD-14-0501]

68 **Bultman SJ**. The microbiome and its potential as a cancer preventive intervention. *Semin Oncol* 2016; **43**: 97-106 [PMID: 26970128 DOI: 10.1053/j.seminoncol.2015.09.001]

69 **Vander Heiden MG**, Cantley LC, Thompson CB. Understanding the Warburg effect: the metabolic requirements of cell proliferation. *Science* 2009; **324**: 1029-1033 [PMID: 19460998 DOI: 10.1126/science.1160809]

70 **Hurez V**, Daniel BJ, Sun L, Liu AJ, Ludwig SM, Kious MJ, Thibodeaux SR, Pandeswara S, Murthy K, Livi CB, Wall S, Brumlik MJ, Shin T, Zhang B, Curiel TJ. Mitigating age-related immune dysfunction heightens the efficacy of tumor immunotherapy in aged mice. *Cancer Res* 2012; **72**: 2089-2099 [PMID: 22496463 DOI: 10.1158/0008-5472.CAN-11-3019]

71 **Schroeder BO**, Birchenough GMH, Ståhlman M, Arike L, Johansson MEV, Hansson GC, Bäckhed F. Bifidobacteria or Fiber Protects against Diet-Induced Microbiota-Mediated Colonic Mucus Deterioration. *Cell Host Microbe* 2018; **23**: 27-40.e7 [PMID: 29276171 DOI: 10.1016/j.chom.2017.11.004]

72 **Hester CM**, Jala VR, Langille MG, Umar S, Greiner KA, Haribabu B. Fecal microbes, short chain fatty acids, and colorectal cancer across racial/ethnic groups. *World J Gastroenterol* 2015; **21**: 2759-2769 [PMID: 25759547 DOI: 10.3748/wjg.v21.i9.2759]

73 **Bridges KM**, Diaz FJ, Wang Z, Ahmed I, Sullivan DK, Umar S, Buckles DC, Greiner KA, Hester CM. Relating Stool Microbial Metabolite Levels, Inflammatory Markers and Dietary Behaviors to Screening Colonoscopy Findings in a Racially/Ethnically Diverse Patient Population. *Genes (Basel)* 2018; **9** [PMID: 29495356 DOI: 10.3390/genes9030119]

74 **Rhee KJ**, Wu S, Wu X, Huso DL, Karim B, Franco AA, Rabizadeh S, Golub JE, Mathews LE, Shin J, Sartor RB, Golenbock D, Hamad AR, Gan CM, Housseau F, Sears CL. Induction of persistent colitis by a human commensal, enterotoxigenic Bacteroides fragilis, in wild-type C57BL/6 mice. *Infect Immun* 2009; **77**: 1708-1718 [PMID: 19188353 DOI: 10.1128/IAI.00814-08]

75 **Wu S**, Morin PJ, Maouyo D, Sears CL. Bacteroides fragilis enterotoxin induces c-Myc expression and cellular proliferation. *Gastroenterology* 2003; **124**: 392-400 [PMID: 12557145 DOI: 10.1053/gast.2003.50047]

76 **Swidsinski A**, Khilkin M, Kerjaschki D, Schreiber S, Ortner M, Weber J, Lochs H. Association between intraepithelial Escherichia coli and colorectal cancer. *Gastroenterology* 1998; **115**: 281-286 [PMID: 9679033 DOI: 10.1016/s0016-5085(98)70194-5]

77 **Martin HM**, Campbell BJ, Hart CA, Mpofu C, Nayar M, Singh R, Englyst H, Williams HF, Rhodes JM. Enhanced Escherichia coli adherence and invasion in Crohn's disease and colon cancer. *Gastroenterology* 2004; **127**: 80-93 [PMID: 15236175 DOI: 10.1053/j.gastro.2004.03.054]

78 **Bonnet M**, Buc E, Sauvanet P, Darcha C, Dubois D, Pereira B, Déchelotte P, Bonnet R, Pezet D, Darfeuille-Michaud A. Colonization of the human gut by E. coli and colorectal cancer risk. *Clin Cancer Res* 2014; **20**: 859-867 [PMID: 24334760 DOI: 10.1158/1078-0432.CCR-13-1343]

79 **Buc E**, Dubois D, Sauvanet P, Raisch J, Delmas J, Darfeuille-Michaud A, Pezet D, Bonnet R. High prevalence of mucosa-associated E. coli producing cyclomodulin and genotoxin in colon cancer. *PLoS One* 2013; **8**: e56964 [PMID: 23457644 DOI: 10.1371/journal.pone.0056964]

80 **Raisch J**, Buc E, Bonnet M, Sauvanet P, Vazeille E, de Vallée A, Déchelotte P, Darcha C, Pezet D, Bonnet R, Bringer MA, Darfeuille-Michaud A. Colon cancer-associated B2 Escherichia coli colonize gut mucosa and promote cell proliferation. *World J Gastroenterol* 2014; **20**: 6560-6572 [PMID: 24914378 DOI: 10.3748/wjg.v20.i21.6560]

81 **Cougnoux A**, Dalmasso G, Martinez R, Buc E, Delmas J, Gibold L, Sauvanet P, Darcha C, Déchelotte P, Bonnet M, Pezet D, Wodrich H, Darfeuille-Michaud A, Bonnet R. Bacterial genotoxin colibactin promotes colon tumour growth by inducing a senescence-associated secretory phenotype. *Gut* 2014; **63**: 1932-1942 [PMID: 24658599 DOI: 10.1136/gutjnl-2013-305257]

82 **Mima K**, Sukawa Y, Nishihara R, Qian ZR, Yamauchi M, Inamura K, Kim SA, Masuda A, Nowak JA, Nosho K, Kostic AD, Giannakis M, Watanabe H, Bullman S, Milner DA, Harris CC, Giovannucci E, Garraway LA, Freeman GJ, Dranoff G, Chan AT, Garrett WS, Huttenhower C, Fuchs CS, Ogino S. Fusobacterium nucleatum and T Cells in Colorectal Carcinoma. *JAMA Oncol* 2015; **1**: 653-661 [PMID: 26181352 DOI: 10.1001/jamaoncol.2015.1377]

83 **Vollmer T**, Hinse D, Kleesiek K, Dreier J. Interactions between endocarditis-derived Streptococcus gallolyticus subsp. gallolyticus isolates and human endothelial cells. *BMC Microbiol* 2010; **10**: 78 [PMID: 20233397 DOI: 10.1186/1471-2180-10-78]

84 **Vaska VL**, Faoagali JL. Streptococcus bovis bacteraemia: identification within organism complex and association with endocarditis and colonic malignancy. *Pathology* 2009; **41**: 183-186 [PMID: 18972318 DOI: 10.1080/00313020802436816]

85 **Beeching NJ**, Christmas TI, Ellis-Pegler RB, Nicholson GI. Streptococcus bovis bacteraemia requires rigorous exclusion of colonic neoplasia and endocarditis. *Q J Med* 1985; **56**: 439-450 [PMID: 4048386]

86 **Eisma RJ**, Spiro JD, Kreutzer DL. Role of angiogenic factors: coexpression of interleukin-8 and vascular endothelial growth factor in patients with head and neck squamous carcinoma. *Laryngoscope* 1999; **109**: 687-693 [PMID: 10334214 DOI: 10.1097/00005537-199905000-00002]

87 **Abdulamir AS**, Hafidh RR, Bakar FA. Molecular detection, quantification, and isolation of Streptococcus gallolyticus bacteria colonizing colorectal tumors: inflammation-driven potential of carcinogenesis via IL-1, COX-2, and IL-8. *Mol Cancer* 2010; **9**: 249 [PMID: 20846456 DOI: 10.1186/1476-4598-9-249]

88 **Abdulamir AS**, Hafidh RR, Mahdi LK, Al-jeboori T, Abubaker F. Investigation into the controversial association of Streptococcus gallolyticus with colorectal cancer and adenoma. *BMC Cancer* 2009; **9**: 403 [PMID: 19925668 DOI: 10.1186/1471-2407-9-403]

89 **Goodrich JK**, Waters JL, Poole AC, Sutter JL, Koren O, Blekhman R, Beaumont M, Van Treuren W, Knight R, Bell JT, Spector TD, Clark AG, Ley RE. Human genetics shape the gut microbiome. *Cell* 2014; **159**: 789-799 [PMID: 25417156 DOI: 10.1016/j.cell.2014.09.053]

90 **Deschasaux M**, Bouter KE, Prodan A, Levin E, Groen AK, Herrema H, Tremaroli V, Bakker GJ, Attaye I, Pinto-Sietsma SJ, van Raalte DH, Snijder MB, Nicolaou M, Peters R, Zwinderman AH, Bäckhed F, Nieuwdorp M. Depicting the composition of gut microbiota in a population with varied ethnic origins but shared geography. *Nat Med* 2018; **24**: 1526-1531 [PMID: 30150717 DOI: 10.1038/s41591-018-0160-1]

91 **Dahmus JD**, Kotler DL, Kastenberg DM, Kistler CA. The gut microbiome and colorectal cancer: a review of bacterial pathogenesis. *J Gastrointest Oncol* 2018; **9**: 769-777 [PMID: 30151274 DOI: 10.21037/jgo.2018.04.07]

92 **Deplancke B**, Gaskins HR. Hydrogen sulfide induces serum-independent cell cycle entry in nontransformed rat intestinal epithelial cells. *FASEB J* 2003; **17**: 1310-1312 [PMID: 12738807 DOI: 10.1096/fj.02-0883fje]

93 **Yazici C**, Wolf PG, Kim H, Cross TL, Vermillion K, Carroll T, Augustus GJ, Mutlu E, Tussing-Humphreys L, Braunschweig C, Xicola RM, Jung B, Llor X, Ellis NA, Gaskins HR. Race-dependent association of sulfidogenic bacteria with colorectal cancer. *Gut* 2017; **66**: 1983-1994 [PMID: 28153960 DOI: 10.1136/gutjnl-2016-313321]

94 **Wu S**, Powell J, Mathioudakis N, Kane S, Fernandez E, Sears CL. Bacteroides fragilis enterotoxin induces intestinal epithelial cell secretion of interleukin-8 through mitogen-activated protein kinases and a tyrosine kinase-regulated nuclear factor-kappaB pathway. *Infect Immun* 2004; **72**: 5832-5839 [PMID: 15385484 DOI: 10.1128/IAI.72.10.5832-5839.2004]

95 **Schwabe RF**, Jobin C. The microbiome and cancer. *Nat Rev Cancer* 2013; **13**: 800-812 [PMID: 24132111 DOI: 10.1038/nrc3610]

96 **Arthur JC**, Perez-Chanona E, Mühlbauer M, Tomkovich S, Uronis JM, Fan TJ, Campbell BJ, Abujamel T, Dogan B, Rogers AB, Rhodes JM, Stintzi A, Simpson KW, Hansen JJ, Keku TO, Fodor AA, Jobin C. Intestinal inflammation targets cancer-inducing activity of the microbiota. *Science* 2012; **338**: 120-123 [PMID: 22903521 DOI: 10.1126/science.1224820]

97 **Nougayrède JP**, Homburg S, Taieb F, Boury M, Brzuszkiewicz E, Gottschalk G, Buchrieser C, Hacker J, Dobrindt U, Oswald E. Escherichia coli induces DNA double-strand breaks in eukaryotic cells. *Science* 2006; **313**: 848-851 [PMID: 16902142 DOI: 10.1126/science.1127059]

98 **Goodwin AC**, Destefano Shields CE, Wu S, Huso DL, Wu X, Murray-Stewart TR, Hacker-Prietz A, Rabizadeh S, Woster PM, Sears CL, Casero RA Jr. Polyamine catabolism contributes to enterotoxigenic Bacteroides fragilis-induced colon tumorigenesis. *Proc Natl Acad Sci U S A* 2011; **108**: 15354-15359 [PMID: 21876161 DOI: 10.1073/pnas.1010203108]

99 **Wang X**, Yang Y, Huycke MM. Commensal bacteria drive endogenous transformation and tumour stem cell marker expression through a bystander effect. *Gut* 2015; **64**: 459-468 [PMID: 24906974 DOI: 10.1136/gutjnl-2014-307213]

100 **Wang X**, Huycke MM. Extracellular superoxide production by Enterococcus faecalis promotes chromosomal instability in mammalian cells. *Gastroenterology* 2007; **132**: 551-561 [PMID: 17258726 DOI: 10.1053/j.gastro.2006.11.040]

101 **Balamurugan R**, Rajendiran E, George S, Samuel GV, Ramakrishna BS. Real-time polymerase chain reaction quantification of specific butyrate-producing bacteria, Desulfovibrio and Enterococcus faecalis in the feces of patients with colorectal cancer. *J Gastroenterol Hepatol* 2008; **23**: 1298-1303 [PMID: 18624900 DOI: 10.1111/j.1440-1746.2008.05490.x]

102 **Shogan BD**, Belogortseva N, Luong PM, Zaborin A, Lax S, Bethel C, Ward M, Muldoon JP, Singer M, An G, Umanskiy K, Konda V, Shakhsheer B, Luo J, Klabbers R, Hancock LE, Gilbert J, Zaborina O, Alverdy JC. Collagen degradation and MMP9 activation by Enterococcus faecalis contribute to intestinal anastomotic leak. *Sci Transl Med* 2015; **7**: 286ra68 [PMID: 25947163 DOI: 10.1126/scitranslmed.3010658]

103 **Zhou Y**, He H, Xu H, Li Y, Li Z, Du Y, He J, Zhou Y, Wang H, Nie Y. Association of oncogenic bacteria with colorectal cancer in South China. *Oncotarget* 2016; **7**: 80794-80802 [PMID: 27821805 DOI: 10.18632/oncotarget.13094]

104 **Popejoy AB**, Fullerton SM. Genomics is failing on diversity. *Nature* 2016; **538**: 161-164 [PMID: 27734877 DOI: 10.1038/538161a]

105 **Ashktorab H**, Daremipouran M, Devaney J, Varma S, Rahi H, Lee E, Shokrani B, Schwartz R, Nickerson ML, Brim H. Identification of novel mutations by exome sequencing in African American colorectal cancer patients. *Cancer* 2015; **121**: 34-42 [PMID: 25250560 DOI: 10.1002/cncr.28922]

106 **Paredes J**, Zabaleta J, Garai J, Ji P, Imtiaz S, Spagnardi M, Alvarado J, Li L, Akadri M, Barrera K, Munoz-Sagastibelza M, Gupta R, Alshal M, Agaronov M, Talus H, Wang X, Carethers JM, Williams JL, Martello LA. Immune-Related Gene Expression and Cytokine Secretion Is Reduced Among African American Colon Cancer Patients. *Front Oncol* 2020; **10**: 1498 [PMID: 32983990 DOI: 10.3389/fonc.2020.01498]

107 **Zeller G**, Tap J, Voigt AY, Sunagawa S, Kultima JR, Costea PI, Amiot A, Böhm J, Brunetti F, Habermann N, Hercog R, Koch M, Luciani A, Mende DR, Schneider MA, Schrotz-King P, Tournigand C, Tran Van Nhieu J, Yamada T, Zimmermann J, Benes V, Kloor M, Ulrich CM, von Knebel Doeberitz M, Sobhani I, Bork P. Potential of fecal microbiota for early-stage detection of colorectal cancer. *Mol Syst Biol* 2014; **10**: 766 [PMID: 25432777 DOI: 10.15252/msb.20145645]

108 **Wong SH**, Kwong TNY, Chow TC, Luk AKC, Dai RZW, Nakatsu G, Lam TYT, Zhang L, Wu JCY, Chan FKL, Ng SSM, Wong MCS, Ng SC, Wu WKK, Yu J, Sung JJY. Quantitation of faecal *Fusobacterium* improves faecal immunochemical test in detecting advanced colorectal neoplasia. *Gut* 2017; **66**: 1441-1448 [PMID: 27797940 DOI: 10.1136/gutjnl-2016-312766]

109 **Guo S**, Li L, Xu B, Li M, Zeng Q, Xiao H, Xue Y, Wu Y, Wang Y, Liu W, Zhang G. A Simple and Novel Fecal Biomarker for Colorectal Cancer: Ratio of *Fusobacterium Nucleatum* to Probiotics Populations, Based on Their Antagonistic Effect. *Clin Chem* 2018; **64**: 1327-1337 [PMID: 29914865 DOI: 10.1373/clinchem.2018.289728]

110 **Zackular JP**, Rogers MA, Ruffin MT 4th, Schloss PD. The human gut microbiome as a screening tool for colorectal cancer. *Cancer Prev Res (Phila)* 2014; **7**: 1112-1121 [PMID: 25104642 DOI: 10.1158/1940-6207.CAPR-14-0129]

111 **Li Q**, Hu W, Liu WX, Zhao LY, Huang D, Liu XD, Chan H, Zhang Y, Zeng JD, Coker OO, Kang W, Ng SSM, Zhang L, Wong SH, Gin T, Chan MTV, Wu JL, Yu J, Wu WKK. Streptococcus thermophilus Inhibits Colorectal Tumorigenesis Through Secreting β-Galactosidase. *Gastroenterology* 2021; **160**: 1179-1193.e14 [PMID: 32920015 DOI: 10.1053/j.gastro.2020.09.003]

112 **Flemer B**, Warren RD, Barrett MP, Cisek K, Das A, Jeffery IB, Hurley E, O'Riordain M, Shanahan F, O'Toole PW. The oral microbiota in colorectal cancer is distinctive and predictive. *Gut* 2018; **67**: 1454-1463 [PMID: 28988196 DOI: 10.1136/gutjnl-2017-314814]

113 **Feng Q**, Liang S, Jia H, Stadlmayr A, Tang L, Lan Z, Zhang D, Xia H, Xu X, Jie Z, Su L, Li X, Li X, Li J, Xiao L, Huber-Schönauer U, Niederseer D, Xu X, Al-Aama JY, Yang H, Wang J, Kristiansen K, Arumugam M, Tilg H, Datz C, Wang J. Gut microbiome development along the colorectal adenoma-carcinoma sequence. *Nat Commun* 2015; **6**: 6528 [PMID: 25758642 DOI: 10.1038/ncomms7528]

114 **Routy B**, Le Chatelier E, Derosa L, Duong CPM, Alou MT, Daillère R, Fluckiger A, Messaoudene M, Rauber C, Roberti MP, Fidelle M, Flament C, Poirier-Colame V, Opolon P, Klein C, Iribarren K, Mondragón L, Jacquelot N, Qu B, Ferrere G, Clémenson C, Mezquita L, Masip JR, Naltet C, Brosseau S, Kaderbhai C, Richard C, Rizvi H, Levenez F, Galleron N, Quinquis B, Pons N, Ryffel B, Minard-Colin V, Gonin P, Soria JC, Deutsch E, Loriot Y, Ghiringhelli F, Zalcman G, Goldwasser F, Escudier B, Hellmann MD, Eggermont A, Raoult D, Albiges L, Kroemer G, Zitvogel L. Gut microbiome influences efficacy of PD-1-based immunotherapy against epithelial tumors. *Science* 2018; **359**: 91-97 [PMID: 29097494 DOI: 10.1126/science.aan3706]

115 **Jain T**, Sharma P, Are AC, Vickers SM, Dudeja V. New Insights Into the Cancer-Microbiome-Immune Axis: Decrypting a Decade of Discoveries. *Front Immunol* 2021; **12**: 622064 [PMID: 33708214 DOI: 10.3389/fimmu.2021.622064]

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**Figure Legends**

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**Figure 1 Tumor-promoting inflammation.** TLRs: Toll-like receptors; BFT: *Bacteroides fragilis* toxin; MAPK: Mitogen-activated protein kinase; *ETBF*: Enterotoxigenic *Bacteroides fragilis*; IL: Interleukin; TNF-α: Tumor necrosis factor α; COX-2: Cyclooxygenase-2; SATA3: Signal transducer and activator of transcription 3; Th17: T-helper-17.



**Figure 2 Avoiding immune destruction.** TIGIT: T-cell immunoglobulin and ITIM domain; NK: Natural killer.



**Figure 3 Deregulating cellular energetics.** SCFAs: Short chain fatty acids.



**Figure 4 Sustaining proliferative signaling.**



**Figure 5 Resisting cell death.** WEA: Wall extracted antigens; PGE2: Prostaglandin E2; IL: Interleukin; COX-2: Cyclooxygenase-2.



**Figure 6 Genome instability.** Colibactin is a genotoxin associated with particular strains of *Escherichia coli*. Sulfidogenic bacteria referred to in this diagram are *Fusobacterium*, *Desulfovibrio* and *Bilophila wadsworthia*. ROS: Reactive oxygen species; RNS: Reactive nitrogen species; H2S: Hydrogen sulfide; CIN: Chromosomal instability; BFT: *Bacteroides fragilis* toxin; MSI: Microsatellite instability; MAPK: Mitogen-activated protein kinase; COX-2: Cyclooxygenase-2.

**Table 1 Gut and gastric microbiota associated with cancer development**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Gut bacteria** | **Bacterial machinery** | **Hallmarks of cancer including enabling characteristics affected** |  **Outcome** | **Methods** | **Ref.** |
| *Fusobacterium nucleatum* | FadA | Tumor-promoting inflammation | Expression of NF-κB and pro-inflammatory cytokines IL-6, 8, and 18 | HCT116 cells (expressing E-cadherin) | [56,57] |
| Unknown | Tumor-promoting inflammation | Infiltration of specific myeloid cell subsets and an NF-κB proinflammatory signature (shared with human CRC tissue with a high Fusobacterium abundance) | Apc(Min/+) mice fed *F. nucleatum* | [39] |
| Unknown | Tumor-promoting inflammation | TNF-α and IL-10 abundance | Rectal biopsies of adenoma cases compared to controls | [59] |
| Unknown | Tumor-promoting inflammation | Cytokine production, which is mediated by the p38 MAPK signaling but independent of TLRs, NOD-1, NOD-2 and NF-ĸB signaling | HEK293T cells, (which lack endogenous TLRs) | [58] |
| Fap2 | Avoiding immune destruction | Fap2 interacted with TIGIT, leading to the inhibition of NK cell cytotoxicity | Various BW cells | [31] |
| Unknown | Avoiding immune destruction | MicroRNA-21 increases the levels of IL-10 and prostaglandin E2, which suppress antitumor T-cell-mediated adaptive immunity | Colorectal carcinoma tissues (stages I-IV) from Japanese patients | [66] |
| Generation of formyl-methionyl-leucyl-phenylalanine and SCFAs from dietary amino acids | Deregulating cellular energetics | Chemoattract myeloid cells | ApcMin/+ mouse model of intestinal tumorigenesis | [39] |
| Adhesin FadA | Sustaining proliferative signaling | FadA binds to E-cadherin and activates β-catenin signaling | HCT116 cells (expressing E-cadherin) | [56] |
| Unknown | Genome instability and mutations | CpG island methylating phenotype (CIMP), microsatellite instability (MSI), and MLH1 hypermethylation | Colorectal carcinoma tissue | [82] |
| *Streptococcus galloyticus* (*S. bovis*) | Unknown | Tumor-promoting inflammation | Increase in the production of IL-8 in the colonic mucosa. Study suggests that bacteria act as a promoter of early preneoplastic lesions in the colon of rats | Male rats pre-treated with the carcinogen azoxymethane (AOM) | [64] |
| Unknown | Tumor-promoting inflammation | Induce mRNA expression of proinflammatory cytokines, IL-1 | Colorectal mucosa and tumors of CRC patients with and without a history of *S. gallolyticus* bacteremia in the last 2 years | [87] |
| Wall extracted antigens (WEA) and whole bacteria | Sustaining proliferative signaling | MAPKs activation which up-regulate the expression of COX-2 | Human colonic epithelial Caco-2-cells | [36] |
| Unknown | Inducing angiogenesis | Induce mRNA expression of angiogenic chemokine, IL-8 | Feces and colorectal tissue of CRC patients with and without a history of *S. gallolyticus* bacteremia in the last 2 years | [87] |
| WEA and whole bacteria | Inducing angiogenesis | Over-expression of COX-2 | Human colonic epithelial Caco-2-cells | [36] |
| Unknown | Resisting cell death | mRNA expression of proinflammatory cytokines, IL-1 and COX-2, as well as angiogenic chemokine, IL-8 | Feces and colorectal tissue of CRC patients with and without a history of *S. gallolyticus* bacteremia in the last 2 years | [87] |
| Unknown | Resisting cell death | Higher IL-8 mRNA and NF-κB mRNA in tumorous than non-tumorous tissue sections of adenoma and carcinoma | Serum and tissue of CRC, CRA and healthy volunteers | [88] |
| WEA and whole bacteria | Resisting cell death | Over-expression of COX-2 | Human colonic epithelial Caco-2-cells | [36] |
| Enterotoxigenic *Bacteroides fragilis* | *B. fragilis* toxin (BFT) | Tumor-promoting inflammation | Activation of STAT3 initiates a Th17 mucosal immune response | ApcMin/+ mouse model of intestinal tumorigenesis | [53] |
| BFT | Sustaining proliferative signaling | E-cadherin cleavage then β-catenin nuclear signaling is expressed and induces c-Myc translation | HT29/C1 cells | [94] |
| BFT | Sustaining proliferative signaling | Induces E-cadherin cleavage, interleukin-8 secretion, and epithelial cell proliferation | Specific pathogen-free (SPF) C57BL/6J or germfree mice | [74] |
| BFT | Genome instability and mutations | NF-κB and mitogen-activated protein kinases (MAPKs) | HT29/C1 cells | [94] |
| BFT | Genome instability and mutations | SMO-dependent generation of ROS and induction of γ-H2A.x, a marker of DNA damage | HT29/c1 and T84 colonic epithelial cells | [98] |
| *E. coli* | Cyclo-modulins (CM) | Sustaining proliferative signaling | Increases in proliferating cell nuclear antigen (PCNA) mRNA levels | CEACAM-expressing mice | [80] |
| Colibactin-producing (pks+) | Sustaining proliferative signaling | Accumulation of SUMO-conjugated p53 and production of hepatocyte growth factor (HGF) by targeting targets SENP1 (senescence-associated secretory phenotype) | AOM/IL-10-/- (azoxymethane/interleukin) mouse model | [81] |
| CM | Genome instability and mutations | genotoxin-encoding genes in mucosa | Analysis of mucosa of patients with CRC | [79] |
| *Enterococcus fecaelis* | Unknown | Genome instability and mutations | Macrophage COX-2 is induced by superoxide and propagate genomic instability | Hybrid hamster cells [A(L)N] containing human chromosome 11 and a dual-chamber tissue culture model | [100] |
| *Enterococcus faecalis*-infected macro-phages, or purified trans-4-hydroxy-2-nonenal (4-HNE)-an endogenous mutagen and spindle poison produced by macrophages | Genome instability and mutations | Double-stranded DNA breaks, tetraploidy and chromosomal instability (CIN) | Primary murine colon epithelial cells growth as allografts in immunodeficient mice | [99] |
| Unknown | Genome instability and mutations | Epithelial cell DNA damage through the production of extracellular O2- | HT-29 intestinal epithelial cells and a rat intestinal colonization model | [12] |
| *H. pylori* | cagA | Tumor-promoting inflammation | Upregulation of COX-2 and prostaglandin E2 | Analysis of serum IgG antibodies against *H. pylori* (ELISA) and cagA protein (Western blot assay) in patients with colon cancer | [62] |

COX-2: Cyclooxygenase-2; *H. pylori*: *Helicobacter pylori*; CIN: Chromosomal instability; CRC: Colorectal cancer; HGF: Hepatocyte growth factor; BFT: *Bacteroides fragilis* toxin; CM: Cyclo-modulins; SATA3: Signal transducer and activator of transcription 3; MSI: Microsatellite instability; PCNA: Proliferating cell nuclear antigen; TLRs: Toll-like receptors; cagA: Cytotoxin-associated gene; *S. gallolyticus*: *Streptococcus gallolyticus*; *S. bovis*: *Streptococcus bovis*.



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