Review

Infectious Agents and Colorectal Cancer: A Review of *Helicobacter pylori*, *Streptococcus bovis*, JC Virus, and Human Papillomavirus

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Abstract

Based on the high volume of bacteria and viruses that the intestine is exposed to and the importance of infectious agents in some gastrointestinal and anogenital cancers, it is not surprising the many studies have evaluated the association between colorectal cancer and infectious agents. This review highlights investigations of four agents in relation to colorectal cancer. *Helicobacter pylori*, *Streptococcus bovis*, JC virus, and human papillomavirus have all been evaluated as possible etiologic agents for colorectal cancer. For each of these agents, a review of possible mechanisms for carcinogenesis and epidemiologic evidence is discussed, and future directions for research are proposed. (Cancer Epidemiol Biomarkers Prev 2008;17(11):2970–9)

Introduction

Since the 1980s, there has been a dramatic increase in research on infections and cancer. In 2002, it was reported that infectious agents accounted for ~18% of all cancers worldwide (1). This estimate is based on the burden of disease associated with cancers that have known infectious etiologies, such as cervical, liver, and gastric cancers. However, as the technology to detect infectious agents improves and more studies are conducted, future research may reveal new associations between cancer and infection, and the proportion of cancers attributable to infection may rise. Furthermore, linking cancers to specific infectious agents may provide new avenues for effective cancer prevention, in particular vaccination.

In 2002, there were ~1 million new cases of colorectal cancer worldwide, accounting for 9.4% of all cancer (2). Colorectal cancer is the fourth most common cancer among men and third most common among women worldwide (2); nonetheless, much is still uncertain about its etiology. It is established that colorectal cancer has a strong association with certain hereditary gene mutations, but only 3% to 5% of colorectal cancers are due to these known mutations alone (3). Cigarette smoking, high alcohol consumption, low vegetable intake, obesity, and physical inactivity are associated with an increased risk of colorectal cancer; postmenopausal hormone use, nonsteroidal inflammatory drug use, and high calcium intake are associated with a reduced risk (4).

Colorectal cancer originates in the epithelial cells lining the colon and rectum. The cells of the human colon replicate at a relatively high rate with 10^{10} epithelial cells being replaced every day (5). This high rate of replication is thought to contribute to the vulnerability of colon and rectal epithelium to mutation and consequent carcinogenesis, although this elevated risk does not seem to apply to the small intestine despite comparably elevated cell turnover. If colonic epithelial cells accumulate mutations in oncogenes and tumor suppressor genes, the morphology of the cell changes, and there is a hyperproliferation of abnormal cells (6). This can result in a neoplastic growth, known as a polyp. Adenomatous polyps (adenomas) are benign lesions in the colon and rectum that have the potential to develop into cancer (7). Other pathways for colorectal cancer include those involving hyperplastic polyps (8-10) and ulcerative colitis (11).

The human intestine provides a habitat that is rich in nutrients, permitting for the growth of over 500 different species of bacteria, with the highest concentration of bacteria found in the colon (12). In addition to bacteria, the human colon is frequently exposed to both pathogenic and nonpathogenic viruses. Normally, the bacteria found in the colon have a symbiotic relationship with their host and can even provide some protection against pathogens (12). However, some microbes that are normally or incidentally found in the colon are pathogenic or potentially pathogenic if they breech the host mucosal barrier.

Due to the sheer numbers of microbes found in the colorectum and the recent interest in infectious agents as a cause of cancer, it is not surprising that researchers have begun, again, to consider infectious agents as a possible cause of colorectal cancer. In this article, we review the evidence on four infectious agents that have

Received 6/20/08; revised 7/16/08; accepted 8/21/08.

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doi:10.1158/1055-9965.EPI-08-0571

been most commonly studied in relation to colorectal cancer: *Helicobacter pylori, Streptococcus bovis*, JC virus (JCV), and human papillomavirus (HPV). For each infectious agent, we conducted a search of PubMed and reviewed all relevant studies with an article or abstract written in English published before 2008.

H. pylori

Infection with *H. pylori* usually occurs at a young age and is extremely common, with one study showing that 49% of the people pooled from 17 populations across the world had antibodies to *H. pylori* (13). However, there is tremendous geographic variation in the prevalence of *H. pylori* infection with some of the highest infection rates nearing 90% in parts of Japan and the lowest infection rates around 33% in the United States (13). In addition, *H. pylori* infection is associated with low socioeconomic status, and person-to-person transmission is thought to be the dominant mode of transmission (14). Also, *H. pylori* infection prevalence varies markedly by age, either as a result of a cohort effect in which older generations were exposed to higher rates of *H. pylori* transmission or (less likely) accumulating risk of infection with age (13).

H. pylori is a Gram-negative bacterium that has become well adapted to the human stomach via interaction with gastric epithelial cells (15). Chronic gastric infection with *H. pylori* causes inflammation and several gastric pathologies, including gastric ulcers and gastric cancer (16-18). Carcinogenesis via *H. pylori* involves inflammation, as well as deregulation of the cell cycle via the *H. pylori* protein, cytotoxin-associated gene A (CagA), which binds and activates SHP2 (a human phosphatase that can act as an oncoprotein) resulting in cell growth and motility (18). Due to the strong association between *H. pylori* and gastric cancer, *H. pylori* is classified as a class I carcinogen by the IARC (19).

Despite the established relationship between *H. pylori* and gastric pathologies, the association between *H. pylori* and colorectal cancer is much less clear. Epidemiologic studies have used serology, PCR methods, C-urea breath tests, and circulating gastrin levels to examine colorectal neoplasia in relation to *H. pylori* infection and have produced conflicting results.

We reviewed 16 epidemiologic studies examining associations between colorectal adenomas or adenocarcinomas and *H. pylori* seroprevalence. Six of these studies found statistically significantly associations between *H. pylori* antibodies and colorectal neoplasia with odds ratio (OR) estimates ranging from 1.4 to 4.0 (20-25). However, the other 10 studies did not find a statistically significant association between *H. pylori* seropositivity and colorectal neoplasia (26-35). Most of these null studies reported OR estimates between 1.0 and 1.5 (26, 28, 30-32, 34, 35). Only one of these studies reported an inverse association between *H. pylori* and colorectal neoplasia [OR, 0.7; 95% confidence interval (95% CI), 0.3-2.0; ref. 27].

A recent meta-analysis examining studies published between 1991 and 2002 to determine the relationship between *H. pylori* and colorectal neoplasia found an overall statistically significant association between *H. pylori* and the risk of colorectal neoplasia (OR, 1.4; 95% CI, 1.1-1.8; ref. 36). However, there is skepticism of this association, because the geographic distribution of colorectal cancer does not mirror that of gastric cancer, and in many areas, most notably in Japan, there are opposing trends over time for these two cancers (37, 38).

Discrepancies in the results between studies could be attributed to differences in the selection of controls, variation in adjustment for confounding variables, and limited power to detect associations due to small sample sizes in most of the studies. However, one study attributes these variable results to differences in the prevalence of CagA+ strains of *H. pylori* between the populations studied (30). Studies of gastric cancer indicate that *H. pylori* CagA+ strains are more likely to cause inflammation and malignancy than CagA- strains (39, 40). Therefore, the Shmuely et al. study compared CagA status between 41 colorectal adenocarcinoma patients seropositive for *H. pylori* and 24 hospital-based controls also seropositive for *H. pylori*. Infection with a CagA+ strain was associated with a statistically significant increased risk of colorectal adenocarcinoma (OR, 10.6; 95% CI, 2.7-41.3) compared with infection with a CagA- strain. Although the design of this study is limited because it is hospital-based rather than population-based, it underscores the importance of examining pathogen characteristics as possible risk factors for disease. Not all *H. pylori* strains have the same virulence, so combining mild strains together with more virulent strains may dilute possible associations.

Although serology is the most common approach used to assess the relationship between *H. pylori* and colorectal cancer, several other techniques have been used. C-urea breath tests can detect current gastric *H. pylori* infection with ~97% sensitivity and specificity (41). A Taiwanese study using this method found no association between current *H. pylori* infection and colorectal adenomas (42). However, another study in Japan using C-urea breath tests, urease detection in biopsy specimens, or other histologic tests of biopsied gastric tissue to assess current infection with *H. pylori* found positive associations (OR, 1.60; 95% CI, 1.18-2.02 for adenomas and OR, 1.80; 95% CI, 1.28-2.32 for adenocarcinomas). This association was modified by sex, with a stronger association among women (43).

Using PCR methods, one study found that 1.2% of malignant colorectal tissues (n = 83) were positive for *H. pylori*, whereas 6.0% of normal tissues were positive (n = 83; ref. 44). Therefore, the authors concluded that *H. pylori* is not important in the pathogenesis of colorectal cancer. However, two other studies that used PCR to detect *H. pylori* in colorectal neoplasms indicated that a much greater proportion of these tissues were positive for *H. pylori*: one study detected *H. pylori* DNA in 27% of colorectal adenocarcinoma tissues (45) and another found that detection of *H. pylori* DNA in colorectal tissue was associated with an increased risk of colorectal adenocarcinomas (OR, 8.13; 95% CI, 1.4-47.0; ref. 46).

It could be that it is not infection of colorectal tissue with *H. pylori* that may be responsible for an increased risk of colorectal cancer but rather the byproducts of a gastric *H. pylori* infection (22). One theory stems from the fact that gastric *H. pylori* infection increases serum levels of gastrin leading to hypergastrinemia (47). Because

hypergastrinemia is hypothesized to have proliferative effects on intestinal mucosa (48), some studies have assessed the relationship between serum gastrin levels and colorectal cancer risk. Several studies found a positive association between hypergastrinemia and colorectal neoplasia (22, 28, 33), including a prospective study assessing serum gastrin levels before the diagnosis of colorectal carcinoma (OR, 3.9; 95% CI, 1.5-9.8; ref. 28).

If *H. pylori* is a cause of colorectal carcinoma, it is clear that the association is complex and perhaps mediated through pathogen-virulence factors. Future research addressing the relationship between *H. pylori* and colorectal neoplasia should be prospective and make attempts to increase the sensitivity of studies by focusing on the subsets of *H. pylori* that are most likely to cause malignancy and/or subsets of colorectal cancers that are most likely to be associated with infection or inflammation. In addition, studies should evaluate gastric *H. pylori* infection as a possible risk factor for colorectal neoplasia.

S. bovis

S. bovis, a nonenterococcal group D *Streptococcus*, is a bacterium that is found among the normal flora of the human gastrointestinal (GI) tract in 5% to 16% of adults (49). In addition, *S. bovis* is commonly detected as a contaminant in packaged meat (50). If *S. bovis* enters the bloodstream, it can cause bacteremia and endocarditis; ~11% to 12% of infective endocarditis are caused by *S. bovis* (51, 52). Endocarditis caused by *S. bovis* is more common in men and in the elderly (53). In two studies, patients with endocarditis caused by *S. bovis* type I, recently reclassified as *Streptococcus gallolyticus*, have an increased risk of prevalent colorectal neoplasia (54, 55).

Laboratory studies of *S. bovis* reveal that this bacterium releases proteins that stimulate inflammation (56). In addition, *S. bovis* proteins were associated with an *in vitro* overexpression of cyclooxygenase-2 (56), which is known to be frequently overexpressed in human colorectal cancers and which can inhibit apoptosis and increase angiogenesis (57).

The debate over the association between *S. bovis* and colonic neoplasia has a long history, going back as early as 1951 when the first case report of colon cancer associated with enterococcal endocarditis was published (58). Since then, numerous studies and case reports have linked *S. bovis* bacteremia and endocarditis with colon polyps and carcinomas (59-72). In a review of studies evaluating patients with *S. bovis* bacteremia who were examined for GI disease, Gold et al. noted that studies reported between 6% and 71% of those with *S. bovis* bacteremia had colonic neoplasia (71). Due to the high prevalence of colonic neoplasia in those with *S. bovis* bacteremia or endocarditis, colonoscopy to screen for occult colorectal cancer and precancerous lesions has been recommended in this group (60, 62, 63, 65, 70, 71).

In addition, several cross-sectional studies have examined the association between *S. bovis* endocarditis and colonic neoplasia. A 1987 study found statistically significantly higher risks of colon polyps and colon cancer among 34 patients with *S. bovis* endocarditis compared with 43 patients with endocarditis caused by other bacteria (35% versus 7% for polyps and 26% versus 2% for cancer; ref. 66). Since then, two additional studies have confirmed these results (68, 69). The Hoen et al. study compared the prevalence of colon polyps and colon cancer in 32 colonoscopy screened cases of *S. bovis* endocarditis and 64 age- and sex-matched controls without *S. bovis* endocarditis also screened via colonoscopy: 47% of *S. bovis* endocarditis patients had colon adenomas versus 23% of those without *S. bovis* endocarditis, and 9% of *S. bovis* endocarditis cases had colorectal cancer compared with 3% of those without *S. bovis* endocarditis (68). The Pergola et al. study examined colorectal neoplasia in 40 cases of *S. bovis* endocarditis and 166 patients with infective endocarditis caused by other bacterium: colorectal neoplasia was present in 55% of *S. bovis* endocarditis cases but in only 4% of other infective endocarditis cases (69). Although the above studies have been small, all suggest an association between *S. bovis* endocarditis and colorectal neoplasia.

Other studies examining the presence of *S. bovis* in stool and the risk of colorectal cancer have produced conflicting results. A study by Klein et al. found that 35 of 63 colon cancer cases had *S. bovis* present in their stool compared with 11 of 105 hospital-based controls (OR, 10.7; 95% CI, 4.8-23.7; ref. 59). This finding was confirmed in a later study on a separate population (73). However, three studies found no association between the presence of *S. bovis* in stool and colorectal neoplasia (74-76).

Serologic studies assessing the association between *S. bovis* antibodies and colonic neoplasia have been done. A 1993 study examining serum samples from 16 colon cancer cases and 16 age-matched controls whose sera was being tested for rheumatoid factor and anti-nuclear factor found that cases had a statistically significantly higher median IgG antibody titer to *S. bovis* than controls; however, IgM antibody titers were similar between the two groups (77). The authors concluded that immune stimulation caused by *S. bovis* occurred over a long period of time and was not a recent occurrence due to advanced clinical disease. Another study by Tjalsma et al. found *S. bovis* antibodies in 11 of 12 colon cancer patients, in 3 of 4 colon polyp patients, and in 0 of 8 control subjects; antibodies to another bacterium commonly found in the human gut, *Escherichia coli*, were not found more commonly in cases than controls (78).

Based on this body of evidence, there is a strong association between *S. bovis* bacteremia and colorectal neoplasia. However, many debate the temporality of this association. One view is that ulcerating colorectal carcinomas allow increased growth of *S. bovis*, invasion of the bloodstream, and establishment of infection (59). Others argue that *S. bovis* is a direct cause of colon carcinogenesis. Supporters of the latter argument point to the fact that precancerous polyps, and not just ulcerative carcinomas, are associated with *S. bovis* (73, 78). Furthermore, a 1982 study found an increased risk of subsequent colonic neoplasia among those with previous *S. bovis* endocarditis (63). Finally, molecular evidence points toward *S. bovis* as a possible carcinogen in a rat model (56, 79).

Despite this evidence, large gaps exist in the literature assessing the relationship between *S. bovis* and colon cancer. There are currently no published case-control studies using PCR to detect *S. bovis* in colorectal tissue from cases and controls. In addition, *S. bovis* type I is the subtype of *S. bovis* that is most commonly associated

with colorectal neoplasia in patients with *S. bovis* bacteremia (54, 55). However, most colorectal cancer epidemiology studies have not classified *S. bovis* according to subtype. Therefore, studies may dilute a possible association by combining the more pathogenic subtype, type I, with less pathogenic subtypes. Finally, large prospective studies are absent from the literature. Because colorectal cancer screening has become relatively common, prospective studies of *S. bovis* colorectal infection and later development of colorectal neoplasia are feasible and should be pursued.

JCV

Human infection with the polyomavirus, JCV, is extremely common, affecting up to 80% of the population (80). Although the route of transmission for JCV is unknown, primary infection generally occurs in early childhood. The vast majority of those infected with JCV have no symptoms, and the virus travels to the kidneys, where it remains latent (81). However, severe immunosuppression, as seen in transplant patients and those with advanced HIV disease, can trigger reactivation of the virus causing a serious demyelinating disease known as progressive multifocal leukoencephalopathy (82, 83).

The oncogenic properties of JCV are well described in the literature and attributed to the viral protein, large T-antigen. Laboratory studies of this viral protein have shown that the large T-antigen has the ability to immortalize cells in culture (84, 85). The mechanism for this cellular transformation has been studied: the large T-antigen binds p53 and members of the pRb family of proteins, thereby blocking tumor suppression and inducing unchecked cellular replication (86, 87). This is hypothesized to result in chromosomal instability, which is common in colon carcinogenesis (88).

Despite molecular evidence showing the potential for JCV to induce carcinogenesis, there is not a strong consensus linking JCV to human cancers. Most of the studies involving JCV and cancer have been conducted in tumors of the central nervous system, and although many detect the presence of JCV in central nervous system tumors, most of these studies have examined only case tissue and did not compare their results with separate disease-free controls (89-91).

Recently, attention has turned to examining JCV in relation to colorectal neoplasia. Several studies have shown the presence of JCV in both normal and neoplastic tissues from the colon and rectum (92-95). One of the earliest studies to detect JCV DNA via PCR in colorectal epithelial tissues was published in 1999. This study found that, although JCV DNA was in both cancerous and normal colon tissue, the viral copy number was statistically significantly higher in the cancerous cells. In addition, these researchers recommended the use of topoisomerase I treatment to improve PCR sensitivity for detecting JCV. Because JCV contains a supercoiled DNA genome, topoisomerase I is thought to relax the supercoiling and allow better detection and amplification of JCV DNA sequences by PCR (92).

Since then, several studies have examined the presence of JCV DNA in colonic tissue using PCR. A study by Ricciardiello et al. in 2000 confirmed the presence of JCV in the upper and lower GI tract using normal GI tissue samples from 33 patients. This study detected JCV DNA sequences in the upper GI for 70.6% of patients and in the lower GI for 81.2% of patients and concluded that infection of the GI track with JCV is common in those without immune suppression (93).

In addition, we reviewed five studies examining colorectal neoplastic tissue detecting JCV DNA in colorectal neoplasias at varying frequencies, finding from 26% to 89% of carcinomas positive for JCV (94-98). Two of these studies also tested colorectal adenomatous tissue from separate patients with adenomas and normal colorectal tissues from controls. One study found JCV infection in 61% of cancerous tissue ($n = 80$), 60% of adenomatous tissue ($n = 25$), and 30% of normal tissue samples from controls ($n = 20$), resulting in an OR (95% CI) of 6.2 (2.4-16.6) comparing neoplastic tissue with normal tissue. This same study found that JCV viral copy numbers were statistically significantly higher in neoplastic colorectal tissue compared with normal colorectal tissue (94). The other study had lower rates of detection for JCV, finding 26% of cancerous colorectal tissue ($n = 23$), 5% of adenomas ($n = 21$), and 0% of normal tissue ($n = 20$) positive for JCV (95).

Two studies found no association between JCV and colorectal cancer using PCR (99, 100). One of these null studies tested 233 cancerous colorectal tissue samples and 233 normal surrounding colorectal tissue samples from the same patients using a laboratory that had never been used previously for JCV or other viral studies; only one normal colorectal specimen was positive for JCV (100). The authors concluded that there is no association between colorectal cancer and JCV and that previous studies detecting JCV in colonic tissue may have had problems with contamination due to the ubiquity of JCV.

Recently, a nested case-control study tested blood samples collected at least 3 months before cancer diagnosis in 386 male cases of colorectal cancer and 386 matched controls and found no association between JCV seropositivity and colorectal cancer (OR, 0.9; 95% CI, 0.7-1.3; ref. 101). Although this test was sensitive for detecting exposure to JCV, it was not specific to the detection of colonic JCV infection. Because JCV infection is so common, it is important to identify infection site.

Despite the inconsistencies in the epidemiologic evidence, there is molecular evidence that the JCV large T-antigen causes chromosomal mutations resulting in chromosomal instability in colonic epithelial cell lines *in vitro* (102). In addition, Ricciardiello et al. showed that a specific subset of JCV, the Mad-1 strain, is the only type of JCV found in the colon and that a specific variant of this strain (a variant lacking a 98-bp repeat) is associated with colorectal cancer (103). If this finding is confirmed, differentiating this subset of JCV from other potentially nonpathogenic types will be important in establishing an etiologic association between JCV and colorectal cancer.

Future studies need to establish a standard, reliable, and reproducible test for the detection of JCV DNA. This test should be evaluated in masked specimens, multiple populations, and different laboratories to ensure the validity of the results. In addition, prospective studies of fecal carriage of JCV in relation to colorectal cancer are absent from the literature. Such studies could help determine specificity, and possibly causality, in the

association between JCV and colorectal cancer if fecal carriage of virulent JCV subtypes occurs before the development of colorectal neoplasia and at higher rates in cases than controls.

HPV

HPV is a double-stranded DNA virus that infects basal-layer epithelial cells through microscopic abrasions or tears (104). There are more than 100 types of HPV, and about 40 of these types are known to infect genital epithelial cells (105). Genital HPV is transmitted via sexual contact and is the most common sexually transmitted infection among Americans ages 15 to 49 years (106, 107). For most people, anogenital HPV infections resolve on their own and have few to no clinically apparent symptoms (108). However, women who are unable to clear cervical HPV infection and are persistently infected with certain types of HPV are at increased risk for the development of cancer (108).

Not all types of HPV are associated with cancer. Currently, types 16, 18, 31, 33, 35, 39, 45, 51, 52, 56, 58, 59, 68, 73, and 82 are classified as ''high-risk'' oncogenic infections (104). Of these, types 16 and 18 are the most common types found in cervical cancer tumors, with one review finding that ~70% of cases were positive for HPV-16, HPV-18, or both (109). HPV infection is a necessary cause of cervical cancer and is associated with other epithelial malignancies, such as oropharyngeal, penile, vaginal, vulvar, and anal cancers (110-112). Although 100% of cervical cancer is attributable to HPV, other anogenital cancers vary in the proportion of site-specific cancer positive for ''high-risk'' HPV (111).

Oncogenic HPV allows for the growth of cancerous cells through the expression of viral proteins E6 and E7. These interfere with tumor suppressor proteins, p53 and pRb, and induce telomerase, thereby immortalizing cells (111). Thus, HPV-related tumors infrequently contain p53 mutations (113). Infection with ''high-risk'' HPV, however, is not sufficient by itself to cause cancer. Additional cellular alterations are necessary for tumorigenesis, and an accumulation of mutations appears to occur over time (111).

Early case-only studies of colorectal neoplastic tissue failed to detect HPV DNA (114-117). However, the sample size in each of these studies was small, ranging from 10 to 50 cases. In addition, HPV detection techniques have improved, and more recent studies of the association between HPV and colorectal neoplasia suggest a positive association.

We reviewed nine case-control studies of the association between HPV and colorectal neoplasia. Studies varied by the type of tissue analyzed, with some including carcinomas, others adenomas, and still others both. In addition, control tissues varied among studies and included adjacent normal tissue from cases, benign colon polyps from separate individuals, and normal colon tissue from disease-free controls. Eight of these studies used PCR techniques to detect HPV DNA in colorectal neoplastic tissues and control tissues (118-125). One study used immunohistochemistry to detect HPV antigen in case and control tissues (126). Despite limited sample sizes in these studies (ranging from 19 to 72 cases), all case-control studies indicated a positive association between HPV infection and colorectal neoplasia. Estimates of the ORs (95% CIs) associated with these studies ranged from 2.7 (1.1-6.2) to 9.1 (3.7-22.3; refs. 119, 124).

In addition to these case-control studies, a recent study found that, among 56 HPV-positive colorectal tumors, only 3.6% contained p53 mutations (127). This is in contrast to the fact that ~50% of all colorectal cancers contain p53 mutations (128). The authors concluded that this is evidence that HPV may contribute to colorectal cancer through HPV-mediated p53 inactivation, thereby simulating a p53 mutation. Based on this, HPV may play a role in the subset of colorectal cancers that lack p53 mutations. This is consistent with studies of oral carcinomas, which find the association with HPV to be strongest in the subset without p53 mutations (129).

Large cohort studies, with sample sizes ranging from 21,222 to 104,760 cases of cervical cancer, have compared colorectal cancer risk in women with a history of cervical cancer to women in the general population (130-132). Two of these studies reported no association between cervical cancer and subsequent colorectal cancer (130, 131). The other study found an increased risk of cancer of the anus/rectum among cervical cancer survivors and an increased risk of colon cancer in women treated with radiotherapy but no increased risk of colon cancer in women who were not treated with radiotherapy (132). This suggests that any increase in the risk of colon cancer among those with previous cervical cancer is related to radiation treatment and not because of a common etiology, HPV, for the two cancers.

Due to the conflicting evidence concerning the association between colorectal cancer and HPV, further investigation is needed. First, there are no studies of colorectal cancer and sexual risk factors, such as number of sexual partners, age at first intercourse, and history of anal intercourse. Because HPV is a sexually transmitted virus, one would expect colorectal cancer to be positively associated with some or all of these sexual risk factors if HPV plays a role in colorectal carcinogenesis. In addition, current case-control studies are small and do not adjust for potential confounding variables, such as age, sex, and smoking status. Finally, no prospective studies have been done to establish the temporal association between HPV and colorectal neoplasia. Therefore, despite some suggestive evidence of an association between HPV and colorectal neoplasia, large, well-designed studies are needed to test this hypothesis rigorously.

Summary and Recommendations

It is notable that studies of colorectal cancer and infection have resulted in at least four possible candidates that may be involved in colorectal carcinogenesis. This lack of specificity between one etiologic agent and colorectal cancer may be a clue that the relationship between colorectal cancer and infection is not due to any of these agents but instead is tied to a general disruption in the microflora of the gut, resulting in an increased susceptibility to pathogenic infection. Several review articles have discussed colorectal health in relation to normal flora in the gut (133-135). This is an area that deserves further investigation, and any studies of this topic should

Table 1. Evaluation of the association between colorectal cancer and *H. pylori*, *S. bovis*, JCV, and HPV using the Bradford Hill criteria

	H. pylori	*S. bovis*	JCV	HPV
Strength	Meta-analysis OR = 1.4 +	ORs for detection of *S. bovis* in stool range from 1.0 to 10.7 +	ORs for JCV DNA in cases vs controls range from 1.0 to 6.2 +	ORs for HPV DNA in cases vs controls range from 2.7 to 9.1 ++
Temporality	Not evaluated 0	Not evaluated 0	Not evaluated 0	Not evaluated 0
Consistency	Most studies OR $\geq$ 1 ++	*S. bovis* endocarditis studies consistently show elevated risks for colorectal neoplasia. However, stool studies of colorectal cancer cases and controls are not consistent. ++	Inconsistent study results +	Early studies do not detect HPV DNA in colorectal neoplastic tissue. Nine recent case-control studies consistently report an increased risk. ++
Specificity	*H. pylori* is a known cause of gastric cancer. +	*S. bovis* is a cause of septicemia and endocarditis. +	JCV is known to cause progressive multifocal leukoencephalopathy. +	HPV is a known cause of several anogenital cancers. +
Biological plausibility	Association between gastrin, gastric *H. pylori* infection, and colorectal cancer is plausible. Direct infection of the colon is unlikely. ++	*S. bovis* is known to inhabit the colon, and molecular studies indicate that *S. bovis* proteins have carcinogenic properties. +++	JCV large T-antigen has carcinogenic properties, but its ability to infect the colon is under debate. +	HPV infects epithelial cells, and its oncogenic properties are well described, but the ability of HPV to enter the colon and rectum is debatable. ++
Coherence	Geographic distribution of colorectal cancer differs significantly from gastric cancer. +	Many colorectal cancers exhibit overexpression of cyclooxygenase-2. *S. bovis* proteins up-regulate cyclooxygenase-2 *in vitro*. +++	JCV is a neurotrophic virus and is very common in the population. +	Colorectal cancer occurs in epithelial cells, but the risk factors for HPV infection are not known for colorectal cancer. +
Biological gradient	No evidence for gastrin. Not evaluated for *H. pylori*. 0	Not evaluated 0	One study finds viral copy number higher in cases than in controls. +	Not evaluated 0
Analogy	*H. pylori* causes gastric cancer. ++	*H. pylori* induces inflammation in the stomach, resulting in cellular proliferation and increased gastric cancer risk. *S. bovis* could have a similar mechanism in the colon. ++	SV40, another polyomavirus, is hypothesized to cause certain human cancers, including brain cancer. However, this has not been proven. +	HPV causes adenocarcinoma in the cervix. ++
Experiment	Not evaluated, but it is possible to treat *H. pylori* infection. 0	Not evaluated, but it is possible to treat *S. bovis* infection. 0	Not evaluated, and currently, it is not possible to prevent JCV through vaccination. 0	Not evaluated, but it is possible through HPV vaccination studies. 0

NOTE: 0, not evaluated; +, weak evidence; ++, moderate evidence; +++, strong evidence.

be especially vigilant in assessing the temporal association between disruptions in the normal flora of the gut and colorectal cancer.

In addition, the HPV and JCV literature is dominated by studies that use PCR to detect viral DNA in colorectal neoplastic tissue. Because PCR is susceptible to false-positive results due to contamination, further tests, such as serologic assays, should be done for exposure assessment. Another criticism of studies comparing tumor tissue in cases with normal tissue in controls is that the two types of tissues are not comparable, and the sensitivity and specificity of PCR-based testing techniques on normal control tissue is unknown. Again, serologic tests would allow for more comparable exposure assessment between cases and controls. However, serologic assays do not identify the site of infection, so site-specific testing is still an important component to evaluating the etiologic relationship between infectious agents and colorectal cancer.

Also, three of the infectious agents reviewed, *H. pylori*, HPV, and JCV, were first evaluated as causes of cancer in other parts of the body, with two of them (*H. pylori* and HPV) having clear positive associations with other cancers. This resulted in a whole host of studies assessing the possible role of these agents in multiple cancers. However, neither HPV nor *H. pylori* is particularly suited to infect the colon, but hundreds of bacterial species that are adapted to colon have not been evaluated as possible causes of colorectal cancer.

Several sets of guidelines for establishing causality between an exposure and disease have been proposed, with one of the most famous of these being the Bradford Hill criteria (136). The Bradford Hill criteria are applied in epidemiologic studies and include the following: strength of the association (often measured by the magnitude of the OR or relative risk estimate), temporality (exposure proceeds disease), consistency of studies, specificity (a one-to-one relationship in which the exposure leads to a single specific outcome), biological plausibility, coherence with prior knowledge, biological gradient (sometimes considered a dose-effect), analogy, and experimentation. A compilation of these criteria can be used to assess the likelihood that an exposure causes an outcome as opposed to being incidentally associated with the outcome. Table 1 summarizes an evaluation of each infectious agent in relation to colorectal cancer using Hill's criteria. Based on Table 1, it is clear that none of these agents show unequivocal, strong evidence for a causal association with colorectal cancer. None have been evaluated to determine if the infectious agent precedes the development of colorectal cancer. In addition, studies that assess viral or bacterial copy number in relation to disease severity, a way to evaluate the biological gradient criteria, are either limited or absent for these infectious agents.

Colorectal cancer clearly does not have one single necessary and sufficient cause. It is almost certain based on existing data that multiple pathways involving host genetics and environmental factors play a role in colorectal cancer carcinogenesis and that subsets of colorectal cancer may be related to particular risk factors. For example, much of colorectal cancer (close to 85% of cases) is characterized by chromosomal instability in which the tumor cells display aneuploidy, an unusual chromosome number (137). However, ~15% to 17% of all colorectal carcinomas are characterized by microsatellite instability with mutations in or methylation of mismatch repair genes (138, 139). This subset appears to be associated with smoking (140), and it is hypothesized that colorectal tumors with chromosomal versus microsatellite instability result from different carcinogenic pathways and may have different etiologies (137).

Future studies of colorectal cancer and infectious agents should attempt to determine the subset of colorectal cancer that is most likely to be associated with the agent of interest, such as by studying the association between the subset colorectal cancer lacking p53 mutations and HPV infection. In addition, future studies should make the assessment of exposure more specific by focusing on the subtype of the agent of interest that is most pathogenic. For example, studies should focus on CagA+ strains of *H. pylori* or *S. bovis* type I instead of collapsing across all subtypes of these organisms. By focusing on more homogenous subsets of disease and subtypes of infectious agents, investigators may be able to increase the sensitivity of their studies to detect associations that may otherwise be masked by competing risk factors and misclassification of exposure status. Also, prospective studies that establish temporality in the relationship between colorectal cancer and infection are necessary for evaluating causality.

Linking cancer to infectious agents has created a whole new direction for cancer prevention. Over the past 100 years, we have witnessed the eradication of infectious disease, such as smallpox, through vaccination, and we have seen the dramatic reduction in other vaccine-preventable diseases, such as measles and polio. With the advent of the hepatitis B vaccine and the more recent HPV vaccine, we are likely to see dramatic decreases in morbidity and mortality due to liver cancer and cervical cancer. Through continued research in infectious agents and cancer, we may observe new associations as well as develop new effective means of prevention.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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Cancer Epidemiol Biomarkers Prev 2008;17:2970-2979.