Antibiotic Treatment Decreases Microbial Burden Associated with Pseudomyxoma Peritonei and Affects β-Catenin Distribution

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Abstract

Purpose: Pseudomyxoma peritonei is an understudied cancer in which an appendiceal neoplasm invades the peritoneum and forms tumor foci on abdominal organs. Previous studies have shown that bacteria reside within pseudomyxoma peritonei tumors and mucin. Thus, we sought to analyze the effect of antibiotics on bacterial density and β-catenin expression within pseudomyxoma peritonei samples.

Experimental Design: The study included 48 patients: 19 with disseminated peritoneal adenomucinosis (DPAM) and 29 with peritoneal mucinous carcinomatosis (PMCA). Fourteen patients were given antibiotics (30 mg lansoprazole, 1 g amoxicillin, and 500 mg clarithromycin) twice a day for 14 days. One week after completion of therapy, surgery was conducted and specimens were harvested for pathology, bacterial culture, ISH, and immunohistochemistry.

Results: ISH showed the presence of bacteria in 83% of the patient samples, with a higher Helicobacter pylori density observed in PMCA versus DPAM. PMCA patients treated with antibiotics had a significantly lower bacterial density and decreased β-catenin levels in the cytoplasm, the cell nuclei, and mucin-associated cells. Although not significant, similar trends were observed in DPAM patients. Cell membrane β-catenin was significantly increased in both DPAM and PMCA patients receiving antibiotics.

Conclusions: Bacteria play an important role in pseudomyxoma peritonei. Antibiotic treatment improved the histopathology of tissue, particularly in PMCA patients. In PMCA, antibiotics decreased bacterial density and were associated with a significant β-catenin decrease in the cytoplasm, cell nuclei, and mucin along with a small membrane increase. These results suggest that antibiotics offer potential protection against cell detachment, cellular invasion, and metastasis. Clin Cancer Res; 19(14); 3966–76. ©2013 AACR.

Introduction

Pseudomyxoma peritonei is characterized by the presence of multifocal peritoneal and omental implants of mucus-secreting epithelial cells and dissecting gelatinous ascites (1). This complex disease is found in 0.02% of laparotomies, and its incidence is threefold higher in females than in males (2, 3). Pseudomyxoma peritonei usually originates from a perforated low-grade appendiceal mucinous neoplasm or appendiceal adenocarcinoma that protrudes into the peritoneum, and the initial presentation of the disease often includes increased abdominal girth and/or appendicitis-like symptoms (4). Pseudomyxoma peritonei can take on a protracted course if the histopathology is that of disseminated peritoneal adenomucinosis (DPAM), or rapidly evolve as a highly malignant tumor with peritoneal mucinous carcinomatosis (PMCA) histopathology. Current treatment combines cytoreductive surgery (resection of the tumor and peritoneal implants) and intraperitoneal hyperthermic chemotherapy (5–8). Despite extensive resections, pseudomyxoma peritonei frequently relapses and 5-year survival is only 53% (9), although survival is significantly better if lymph nodes are negative (5-year survival is 76% for lymph node-negative patients and 11% for lymph node-positive patients; P < 0.001; ref. 10). Even in patients with low-grade appendiceal mucinous neoplasms, most patients succumb to the disease due...
Translation Relevance

Pseudomyxoma peritonei is an underresearched abdominal cancer that originates from an appendiceal neoplasm. Patients frequently relapse and succumb to the disease, necessitating the development of novel therapeutics to treat patients. Recent studies have indicated the presence of bacteria within the tumors and mucin of pseudomyxoma peritonei patients. The study herein indicates that antibiotic treatment significantly reduces bacterial density along with β-catenin levels in the cytoplasm, the cell nuclei, and mucin-associated cells of peritoneal mucinous carcinomatosis (PMCA) patients. In addition, the β-catenin levels within membranes significantly increase in both disseminated peritoneal adenomucinosis and PMCA patients. The normalization of β-catenin distribution combined with the reduction in bacterial density make antibiotic treatment a potential therapeutic for pseudomyxoma peritonei disease.

to recurrent mucoid ascites, proliferation of gelatinous mucin, and mechanical compression and obstruction of abdominal organs, heart, and lungs (11).

A key aspect of colon cancer and several other cancers is deregulation of the Wnt/β-catenin pathway (12). The transmembrane protein β-catenin is associated with the cytoplasmic region of E-cadherin within adherens junctions. In normal, polarized gut epithelial cells, β-catenin provides a linkage mechanism between cytoskeletal proteins and cell-to-cell junctional proteins (e.g., E-cadherin), allowing cells to tightly bind to each other (13). These interactions are crucial for maintenance of epithelial cell polarity, regulation of cell growth, and cell-to-cell focal adhesion. During carcinogenesis, β-catenin relocalizes into the cytoplasm and nucleus. Loss of membrane β-catenin leads to cell separation and migration, movement of abnormal neoplastic cells to the stroma, entry into blood vessels, and metastatic spread to different tissues through the bloodstream (14). Furthermore, following nuclear translocation, β-catenin interacts with T-cell factors (TCF) or lymphocyte-enhancer factors that can then act as transcription factors. Thus, β-catenin nuclear localization triggers expression of various genes, including genes required for cell proliferation (15).

Several infectious agents have been found to stimulate cell proliferation via the Wnt/β-catenin pathway. In fact, the potential for certain viruses to cause cancer has been recognized for some time. Recent studies suggest that Epstein–Barr virus, Kaposi’s sarcoma-associated virus, and hepatitis C virus promote carcinogenesis by activating the Wnt/β-catenin pathway (16, 17). Some bacteria also influence the Wnt/β-catenin pathway. Helicobacter pylori expresses numerous virulence factors that promote carcinogenesis, including the cytotoxin-associated gene A (CagA). Translocation of CagA into epithelial cells results in changes in expression of β-catenin (18) as well as causes nuclear accumulation of β-catenin (19), which is associated with aggressive and invasive tumors (20). Salmonella and Chlamydia trachomatis also stimulate epithelial proliferation via the Wnt/β-catenin pathway (21, 22).

Although pseudomyxoma peritonei patients have no symptoms of peritonitis, we previously hypothesized that intestinal bacteria spread to the peritoneum at the time of appendiceal perforation. In keeping with this idea, we recently showed that H. pylori and other bacteria can be detected in pseudomyxoma peritonei tissues (23). Given this finding, herein we studied the effect of preoperative antibiotic therapy on bacterial density, and on the concurrent expression of β-catenin within the neoplastic cancerous cells of DPAM and PMCA patients. We observed that after antibiotic treatment, PMCA patients showed a significant decrease in bacterial density along with significantly decreased β-catenin expression in the cytoplasm, nuclei, and mucin. We found that in neoplastic cancerous cells, β-catenin is redistributed into the cytoplasm and accumulates in different areas of the cytosol and ground substance (connective tissue in the stroma that supports fibers). En masse, our data suggest that antibiotic treatment of PMCA may affect the carcinogenic pathway elicited by β-catenin and may serve as a novel treatment of this understudied cancer.

Materials and Methods

Patients, histopathology, and treatment

Forty-eight patients with the diagnosis of peritoneal dissemination of appendiceal mucinous neoplasms that had been scheduled to undergo laparotomy for staging, extensive cytoreductive surgery, and hyperthermic intraperitoneal chemotherapy were studied. Patients’ age was 53 ± 2 years and weight 73 ± 2 kg (means and SEM).

Observation and analysis of biopsies stained with hematoxylin and eosin (H&E) from cytoreductive surgical specimens by a board certified and experienced pathologist allowed tumor classification as either DPAM or as the more malignant PMCA (24). Tissue from a patient with a non-perforated, nonneoplastic appendix (NNA) was used as a control. Analysis of the grade of inflammation was conducted according to conditions previously described (25).

Three weeks before surgery, an open label anti-H. pylori triple therapy (PrevPac, i.e., 30 mg lansoprazole, 1,000 mg amoxicillin, and 500 mg clarithromycin given twice a day for 14 days) was given to a total of 14 of the pseudomyxoma peritonei patients: 6 DPAM and 8 PMCA. A total of 34 patients received no antibiotics and were maintained as untreated controls: 13 DPAM and 21 PMCA. One week after completion of the antibiotic therapy, patients and controls underwent cytoreductive surgery (resection of the tumor and peritoneal implants) and hyperthermic intraperitoneal chemotherapy to achieve complete or near-complete resection of pseudomyxoma peritonei cancerous tissues (8).

ISH studies

Probes. Two previously described 16S rDNA bacterial probes (23) labeled with biotin were as follows: (i) a probe...
that can detect 19,973 typed and nonculturable bacteria (TNCB; including *Campylobacter jejuni*, *Escherichia coli*, *Salmonella enterica*, *H. pylori*, and *Enterococcus faecalis*; 5′-AGCAAA CAG GAT TAG ATA CCC TGG TAG TCC AGCCT TAG TCC CCC TGC TCC AC-3′); and (ii) a probe specific for *H. pylori* (5′-ATT TCA CAC GTG ACT GAT CCC TGC TCC CCC TAG GCC-3′; ref. 26). In initial experiments, we used both cRNA and cDNA probes concurrently, and confirmed earlier observations that these 2 probes can detect the same bacteria (27).

Paraffin blocks of formalin-fixed tissue were sectioned (5 µm) and analyzed as previously described (27). Briefly, each unstained section was deparaffinized, prehybridized, hybridized with denatured probe solution, and then incubated for 18 hours with a probe labeled with biotin followed by the removal of unbound probe using saline citrate solution. DNA was detected by incubating the slide for 2 hours with streptavidin-conjugated alkaline phosphatase (Roche Diagnostic; 1:500 dilution in blocking immuno-Tris buffer), washing, and applying, the chromogenic substrate BCIP/NBT/kit (5-bromop-4-chloro-3-indolyl phosphate/nitro-blue-tetrazolium), yielding a blue color reaction (Vector Labs). The slide was then counterstained with Nuclear Fast Red, washed in water, dehydrated, xylene, air dried, and mounted with permount. TNCB and *H. pylori* 16S rDNA were detected in serial sections under bright light as follows: first section: detection of TNCB 16S rDNA, second section: detection of *H. pylori* 16S rDNA. Parallel dual FISH studies (27) were also conducted using the 16S rDNA-TNCB probe labeled with biotin and then detected with avidin labeled with fluorescein–fluorescin isothiocyanate (FITC; green reaction), and the 16S rDNA-*H. pylori* probe labeled with digoxigenin and then detected with anti-digoxigenin mouse monoclonal antibody conjugated to biotin (Abcam) and then detected using avidin–Tx red (red reaction). Colocalization of both TNCB and *H. pylori* was visualized as yellow.

As previously described (27), control for nonspecific binding included: (i) sense probe instead of antisense probe, (ii) hybridization buffer instead of the antisense probe, (iii) unlabeled antisense probe, (iv) digoxigenin or biotin-labeled probe for a sequence completely unrelated to man and prokaryotes—the scorpion *Buthus martensi* Karsch neurotoxin sequence (5′-GGCAACGGCTGAGTCGACTGATC-3′; ref. 28), (v) RNase A pretreatment (Roche), (vi) DNase I pretreatment (Roche), and (vii) RNase + DNase I pretreatment.

For fluorescence, a Nikon Eclipse 80i microscope DS black-white camera with a DS-L2 control unit was used and software from NIS-Elements Advanced Research was used for analysis and reproduction of β-catenin images. For brightfield microscopy, an Eclipse 800 Nikon microscope with digital camera (QCapture Pro, Micropublisher 6.0; Burnaby) was used for analysis and reproduction of bacterial images (TNCB and *H. pylori*). Fluorescence immunohistochemistry (FIHC) was used for studies of β-catenin. Two different studies were conducted:

**Laser confocal microscopy** was used to quantify cell membrane and nuclear localization of β-catenin. Antigen retrieval was first achieved by sequentially treating paraffinized sections with saline citrate solution in a pressure cooker system for 9 minutes (27). β-Catenin expression was analyzed using a mouse anti-β-catenin monoclonal antibody (Santa Cruz Biotechnology, Inc.) at 1:150 dilution followed by biotinylated anti-mouse immunoglobulin G and avidin, labeled with either FITC for β-catenin cell membrane localization or Texas red for β-catenin nuclear localization. For nuclear localization, DNA was also stained using 4,6-diamino-2-phenylindole (DAPI) because it specifically binds DNA without overlap with fluorochromes. Importantly, DAPI binds DNA (heterochromatin and euchromatin) of an interphase nucleus. In contrast to usual dual-fluorescence stains, DAPI stain cannot be easily merged with the expression of any fluorochrome (in this case with β-catenin-Texas red) to produce a third color because nuclear DNA is bound to β-catenin (first layer of procedure) and, as a result, DAPI binding to DNA is not as efficient at the same site. However, DAPI can bind to DNA that is not bound to β-catenin.

**β-Catenin compartment localization** was determined from standard fluorescence (FIHC) of paraffin sections mounted with Vectashield alone (w/o DAPI) and observed using a Nikon Eclipse 80i microscope as described earlier. The following tissue types were analyzed: (i) epithelia; (ii) lymphocytes, monocytes, and granulocytes; (iii) stroma (connective tissue, vessels, fibroblasts, and fibers); and (iv) mucin pools. In addition, specific analyses of (i) lateral cell–cell contact and (ii) cytoplasm localization were conducted.

Fluorescence IHC images were observed and reproduced using the same microscope and digital camera described earlier for the ISH studies.

For β-catenin nuclear localization, sections were mounted using Vectashield containing DAPI and confocal images were collected on a Zeiss S710 NLO laser scanning confocal microscope (Carl Zeiss) equipped with a 63× oil immersion lens (1.4NA). DAPI-stained samples were excited with a 405-nm laser diode and emitted light in the 410 to 556 nm range was collected. For Texas red–stained samples, a laser line of 561 nm was used for excitation and light between 566 and 690 nm was used for imaging (BIC, USUHS). Phosphate buffer solution instead of the first β-catenin antibody was used as a negative control.

**Morphometric analysis**

**Quantitation of bacteria and β-catenin.** Determination of bacterial and β-catenin density in cellular compartments was conducted as previously described (27). Briefly, an intraocular grid-based method was used to examine samples by a microscopist who was blinded to the histopathologic diagnoses (i.e., DPAM or PMCA) as well as antibiotic treatment category. The number of bacterial clusters expressing 16S rDNA of TNCB and/or *H. pylori* was quantified at 400× magnification in 3 randomly selected fields of view according to a modification of the point-counting stereological method, and using an intraocular reticle of 27-mm diameter, covering 3578 m2 (i.e., 17,892 m2 for 5-µm-thick sections; Kr409, Klarmann Rulings, Inc.; ref. 23). Counting of the number of intersections of vertical and horizontal lines that overlapped a bacterium in the area...
delimited by a projected grid on the tissue was conducted. All data were expressed as means ± SEM number of bacteria per $10^6 \mu m^3$ (representing an imaginary cube with sides of 100 $\mu m$ or 0.1 mm).

Total $\beta$-catenin density in biopsies was determined in a similar fashion and expressed as Vvi (volumetric density or volume occupied for the $\beta$-catenin reaction) in $10^6 \mu m^3$ of tissue.

**Computerized quantification of $\beta$-catenin in the nuclei.**
Nuclear localization of $\beta$-catenin and analysis were conducted using a Zeiss 710 NLO laser scanning confocal microscope (Carl Zeiss) as described earlier (BIC, USUHS).

Software developed by TM using a MATLAB platform and associated toolboxes (http://www.mathworks.com/) was used to quantify the fraction of the nuclei occupied by $\beta$-catenin in confocal microscopic pictures of IHC sections that had been double stained for both $\beta$-catenin (Texas red) and DNA (DAPI; Supplementary Methods). In brief, the percent of nuclei volume occupied by $\beta$-catenin was calculated as the number of bright red pixels that overlapped the dark blue DAPI stain divided by total nuclei pixels (nuclei in blue) multiplied by 100.

**Statistical analysis**
Statistical significance was determined using $t$ tests to compare results in patients receiving antibiotics versus no antibiotics in each cell of the tables. Values were expressed as means ± SEM.

**Results**

**Pathological evaluation of DPAM and PMCA**

H&E-stained sections were examined to determine the histopathology of the pseudomyxoma peritonei samples. Sections from DPAM patients (Fig. 1A) showed the presence of abundant extracellular mucin (pale pink areas with blue streaks) surrounded by dark pink collagen bands. Mucin pools were surrounded by connective tissue septa supporting the mucin deposits. Strips of mucinous epithelial lining and scattered chronic inflammatory cells, including lymphocytes and macrophages, were also characteristics of DPAM (Fig. 1A, left). Low-grade adenomatous dysplasia was seen without evidence of mitosis, which is consistent with the more indolent nature of DPAM. Mesothelial hyperplasia, vascular congestion (engorged blood vessels), and chronic inflammation were present in the peritoneal lining adjacent to extracellular mucin in DPAM sections (Fig. 1A, right).

In PMCA patient sections (Fig. 1B–D), glands consisting of angulated gland-forming mucinous epithelium were frequent, often with destructive stromal invasion (Fig. 1B). High-grade cytologic atypia, mitotic activity (Fig. 1C), and

![Figure 1.](https://www.aacrjournals.org/doi/figure/10.1158/1078-0432.CCR-13-0616)
inflammatory cells within a desmoplastic stroma with fibrotic adhesions differentiate PMCA from DPAM (Fig. 1D); desmoplasia is a fibrotic reaction to malignant cells invading normal tissue. No significant differences in inflammatory cell densities were observed across the 2 disease types in H&E slides (scores of 0–3; ref. 29).

Presence of bacteria in DPAM and PMCA as determined by ISH

Our work has previously shown that \( H. \) pylori and other bacteria can be found in pseudomyxoma peritonei samples (23). We therefore sought to confirm these results using these independently obtained pseudomyxoma peritonei samples and ISH with probes that detect TNCB or \( H. \) pylori. Our initial qualitative analysis of samples from all 48 patients revealed that clusters of TNCB (Fig. 2A–C, left) and \( H. \) pylori (Fig. 2A–C, right) were present within 83% of the specimens: 76.9% of the untreated DPAM patients, 83.3% of the antibiotic-treated DPAM patients, 90.5% of the untreated PMCA patients, and 75% of the antibiotic-treated PMCA patients (Table 1). Both TNCB and \( H. \) pylori were present in mucinous epithelium and were associated with mucin-secreting and goblet cells, as well as pools of mucin. Figure 2B (left) shows TNCB bacteria within mucin deposits and in areas of abnormal neoplastic epithelia. \( H. \) pylori was similarly located in the mucin surrounded by abnormal neoplastic epithelia and goblet cells and attached to the cell membrane of neoplastic cells (Fig. 2B, right, and inset). TNCB and \( H. \) pylori were also observed in the connective tissue of the lamina propria (stroma; Fig. 2C, left and right, respectively), touching inflammatory cells located in the stroma, and surrounding epithelial cells in the intestinal glands.

To determine whether there was any effect of antibiotic treatment on the quantity of bacteria found per sample, individual bacteria were counted manually in 3 fields of view. As with the qualitative analysis, \( H. \) pylori and TNCB were detected in 83% of the patients. The 8 patients negative for both probes were as follows: 1 DPAM-A, 3 DPAM-noA, 2 PMCA-A, and 2 PMCA-noA, where “A” indicates antibiotic treatment and “noA” indicates no antibiotic treatment. On average, and as previously reported (23), \( H. \) pylori and TNCB densities were significantly higher in PMCA than in DPAM patients (\( H. \) pylori: 32.4 ± 5.2 vs. 13.0 ± 3.2 \( \times 10^6 \) \( \mu \)m\(^3\), \( P < 0.008\); TNCB: 63.3 ± 10.4 vs. 26.8 ± 5.4 \( \times 10^6 \) \( \mu \)m\(^3\), \( P < 0.01\)). In addition, \( H. \) pylori and TNCB densities were significantly lower in PMCA patients who received preoperative antibiotics (\( H. \) pylori 12 ± 6 vs. 40 ± 6 \( \times 10^6 \) \( \mu \)m\(^3\), \( P < 0.01 \) and TNCB 18.6 ± 7.4 vs. 80.4 ± 12.2 \( \times 10^6 \) \( \mu \)m\(^3\), \( P < 0.006\), respectively). However, there was no significant difference in bacterial density in DPAM patients after antibiotic treatment. Examples of the bacterial density with and without antibiotic treatment are illustrated in an area of pooled mucin using FISH staining (Fig. 3A–C; A: TNCB, B: \( H. \) pylori, C: merge). The TNCB probe binds to \( H. \) pylori as well as other species. Therefore, \( H. \) pylori overlaps TNCB and appears yellow when the images are merged, whereas non-\( H. \) pylori bacteria remain green in the merged image.

### Table 1. Bacterial distribution in pseudomyxoma peritonei samples

<table>
<thead>
<tr>
<th>Group</th>
<th>% of samples containing bacteria</th>
<th>Relative number of ( H. ) pylori</th>
<th>Relative number of TNCB</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPAM</td>
<td>76.9</td>
<td>14.46</td>
<td>29.54</td>
</tr>
<tr>
<td>DPAM, antibiotic treated</td>
<td>83.3</td>
<td>9.90</td>
<td>21.0</td>
</tr>
<tr>
<td>PMCA</td>
<td>90.5</td>
<td>40.37</td>
<td>80.36</td>
</tr>
<tr>
<td>PMCA, antibiotic treated</td>
<td>75</td>
<td>11.54</td>
<td>18.54</td>
</tr>
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</table>
The above results were obtained using probes that recognize 16S rDNA, which detects both live and dead bacteria. Because it was possible that some dead bacteria could still be detected, we evaluated *H. pylori* viability in a subset of PMCA patients using a 16S rRNA probe combined with polyclonal anti-*H. pylori* antiserum. As shown in Supplementary Fig. S1, virtually all of the *H. pylori* were alive in untreated PMCA patients, whereas very few remained viable in antibiotic-treated patients. These data suggest that the determined densities of bacteria are likely artificially high in patients that received antibiotic treatment.

**β-Catenin in pseudomyxoma peritonei**

Given that the Wnt pathway and β-catenin have been shown to be important in numerous forms of cancer, we investigated whether β-catenin quantities and localization were affected in pseudomyxoma peritonei and across pseudomyxoma peritonei types. We assessed this by initially quantifying total β-catenin in 5 random fields per sample from an NNA control and in the DPAM and PMCA sections. When all DPAM and PMCA cases were compared regardless of antibiotic treatment status, we observed that total β-catenin expression tended to be lower in DPAM than in PMCA (1,721 ± 297 vs. 3,083 ± 542 Vvi/10^6 μm^2; *P* < 0.062; NS). When the antibiotic treatment state was taken into consideration across the disease states, antibiotics tended to decrease total β-catenin expression in PMCA patients (*P* < 0.036). However, expression was not significantly different in DPAM patients (*P* < 0.36; NS). Given that localization of β-catenin is crucial to its function inside the cell, we next examined localization within different cellular compartments qualitatively as well as quantitatively. Analysis of β-catenin staining within the NNA control indicated the presence of β-catenin in cell membranes and the lateral junctional complex (Fig. 4A and inset). In contrast, biopsies obtained from PMCA patients that did not receive antibiotics showed virtually no β-catenin staining at the intercellular boundary (Fig. 4B and inset); staining seems primarily cytoplasmic. However, as was noted with the total β-catenin assay, antibiotic treatment seemed to have some effect on β-catenin localization because a moderate to intense reaction was observed in the junctional complexes between some of the PMCA neoplastic cells after antibiotic treatment (Fig. 4C and inset). However, these values did not reach statistical significance when the junctional staining was quantitated for PMCA-A (451 ± 67 Vvi/10^6 μm^2) and compared to PMCA-noA (751 ± 207 Vvi/10^6 μm^2; *P* < 0.36). Antibiotics decreased β-catenin expression in the cytoplasm of PMCA patients who received treatment as compared to no antibiotics (739.9 ± 63.1 vs. 216.6 ± 41.5 Vvi/10^6 μm^2; *P* < 0.0001). When considered as a whole, β-catenin was increased in the stromal compartment of PMCA (A + noA; 1046.5 ± 193.4 Vvi/10^6 μm^2) as compared to DPAM (A + noA; 516.8 ± 70.1 Vvi/10^6 μm^2; *P* = 0.0369). This was especially true in the desmoplastic reactions of untreated PMCA patients (Fig. 4D). Finally, β-catenin levels found within the mucin, presumably due to the presence of infiltrating inflammatory cells, decreased in PMCA patients after antibiotic treatment (464.58 ± 139.418 Vvi/10^6 μm^2) as compared to no antibiotics (2,179.70 ± 303.38 Vvi/10^6 μm^2; *P* < 0.0021). Conversely, DPAM did not show a significant difference in the mucin due to antibiotic treatment. As a result, there was a significant difference (*P* < 0.005) in the overall β-catenin staining of PMCA (A + noA) mucin (1,706.56 ± 264.45 Vvi/10^6 μm^2) as compared to DPAM (A + noA) mucin (433.14 ± 104.55 Vvi/10^6 μm^2). Finally, although some change in β-catenin distribution was seen in the stromal region of PMCA patients, these changes were not significant.

Given that β-catenin is known to enter the nucleus and function as a transcription factor, and because our initial
staining did not allow us to discern which portion of the cytoplasmic β-catenin was actually in the nucleus, we used dual staining with DAPI and β-catenin along with a computerized quantification method to determine the fraction of the nucleus occupied by β-catenin. Control NNA tissue exhibited intense bright DAPI staining, but was negative for nuclear β-catenin (data not shown). Conversely, nuclear β-catenin was common in both PMCA and DPAM samples, as exemplified by the fluorescent staining of the nuclei shown in Fig. 5. In the high magnification insets, bright red color signifies β-catenin expression (A, arrow), whereas dark blue DAPI staining is seen when nuclear β-catenin is absent (B, arrowhead). When the images are merged (C), the intense red shows up without being affected by the blue DAPI stain. Of note, faint perinuclear β-catenin staining is seen around most DAPI-stained nuclei, indicating that β-catenin was present elsewhere in those cells. The percent of DAPI-stained nuclei occupied by β-catenin was not significantly different when all PMCA samples (A + NoA) were compared to DPAM samples (A + NoA) (20.8 ± 2.9% vs. 16.5 ± 3.5%, P < 0.451; NS). However, administration of antibiotics resulted in a significant decrease in the percent of nuclear β-catenin present in PMCA (from 23.8 ± 3.4% to 11 ± 4.4%, P = 0.048). Despite the fact that there was a strong trend toward decreased nuclear β-catenin, this significant difference was not seen with DPAM (from 18.9 ± 4.8% to 11.3 ± 3%, P < 0.152; NS; Fig. 6A). As nuclear β-catenin dropped as a result of antibiotic treatment, the percentage of β-catenin located in the membrane as compared to the cytoplasm increased (Fig. 6B). This rise in membrane β-catenin was significant for both PMCA and DPAM patients.

Figure 4. Qualitative assessment of β-catenin localization in pseudomyxoma peritonei samples. Formalin-fixed tissue samples from pseudomyxoma peritonei patients and an NNA control were sectioned and stained with an anti-β-catenin antibody. The NNA control (A) displayed strong staining at the boundaries between adjacent cells, showing the localization of β-catenin to cell membranes and the lateral junctional complex. Conversely, PMCA sections (B) exhibited primarily cytoplasmic staining of β-catenin and virtually no staining at the intercellular boundaries. Some staining was observed between PMCA neoplastic cells following antibiotic treatment (C). β-Catenin was very visible in the desmoplastic reactions within the stromal compartment of untreated PMCA patients (D).

Figure 5. Immunofluorescence analysis of nuclear β-catenin. Formalin-fixed tissue samples from pseudomyxoma peritonei patients were sectioned and dual stained with an anti-β-catenin antibody and DAPI to observe the localization of nuclear β-catenin. As shown in A, bright red staining (arrow) indicates the presence of β-catenin, whereas B reveals the dark blue DAPI staining (arrowhead) appearing when β-catenin staining is absent. The merged image in C exhibits the intense red β-catenin staining unaffected by blue DAPI staining.
The reduction in nuclear 

expression and cellular distribution after antibiotic 
treatment (36, 37), we have investigated the 
molecular mechanisms by which bacteria may influence 

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molecular mechanisms by which bacteria may influence 
pseudomyxoma peritonei development. Importantly, our 

studies provide the first mechanistic data on the role of 
bacterial infection and β-catenin in pseudomyxoma perito-

cell-to-cell junctions, but it can also influence gene transcription within 
the nucleus. Translocation of β-catenin to the nucleus 
through its association with the Wnt signaling pathway is 
very important in embryogenesis and stem cell mainte-
nance; however, it also contributes to abnormal prolif-
eration during carcinogenesis. Indeed, the heterogeneous 
distribution of β-catenin within tumors suggests crosstalk 
between tumor cells and the tumor microenvironment, 
including epithelial–mesenchymal interaction and the 
vasculature (38). Moreover, in cancer, Wnt-β-catenin-TCF 
signaling plays an important role in nuclear β-catenin 
accumulation (39), but the mechanisms governing this 
translocation are poorly understood and controversial 
(40).

Given the established role of β-catenin in carcinogen-

esis, it was pertinent to investigate the effect of antibiotic 
treatment and reduction in bacterial density on β-catenin 
expression and localization. Careful analysis of β-catenin 
expression and cellular distribution after antibiotic treat-

ment targeted against H. pylori infection revealed impor-
tant reductions in nuclear and total β-catenin levels in 
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treatment reached statistical significance primarily in PMCA samples and not in DPAM samples, which could be the result of the small sample size (n = 6) of antibiotic treated DPAM patients, making it more difficult to reach statistical significance; similar trends were seen in both groups of antibiotic-treated patients. The levels and localization of β-catenin were also altered throughout the various cell types within the analyzed peritoneal tissue, where antibiotic treatment significantly decreased β-catenin expression in the cytoplasm of epithelial and inflammatory cells, in the nuclei, and in the mucin of PMCA patients. Although not statistically significant, stromal β-catenin localization was elevated in PMCA patients not treated with antibiotics. Increased levels of β-catenin within the stroma is associated with desmoplastic reaction in malignancy (Fig. 4D), where β-catenin is attached to the fibrous elements of connective tissue of the stromal compartment (41). The stromal compartment plays an important role during neoplastic cell invasion, detaching from neoplastic intestinal glands, invading the stromal blood vessels and lymphatics, and initiating metastasis (42). β-Catenin within mucin was higher in PMCA patients as compared to DPAM patients. Unlike the stroma, antibiotic treatment had a significant effect on decreasing β-catenin in the mucin. Because mucin is the most important histopathology hallmark of pseudomyxoma peritonei, decreased levels of β-catenin within mucin after antibiotic treatment suggests that antimicrobials might be useful in the treatment of this disease. The effectiveness of antibiotic treatment is further evidenced by the significant elevation of β-catenin levels within the membrane in both PMCA and DPAM patients accompanied by a reduction in nuclear β-catenin levels following administration of antibiotics. In normal cells, the β-catenin complex is present within the adherens junctions, as confirmed by immunogold and transmission electron microscopy (43, 44). β-Catenin within the membrane promotes cell-to-cell communication and is likely to reduce neoplastic cell migration toward the stroma and metastasis; thus, increased levels of β-catenin within the membrane could be helpful in improving the prognosis of pseudomyxoma peritonei disease. Moreover, the renormalization of β-catenin distribution in PMCA patients after antibiotic treatment confirms the pivotal contribution of bacteria to the pseudomyxoma peritonei disease process.

Targeting nuclear β-catenin is a potential strategy for cancer therapy. Other reports have discussed the benefit of using antimicrobial agents to treat cancer; however, most attribute normalization of β-catenin with specific effects of antimicrobial agents on the Wnt/β-catenin pathway unrelated to the killing of microorganisms. For example, patients with ovarian endometrial adenocarcinoma receiving rapamycin had demonstrated inhibition of the Wnt/β-catenin pathway along with a decrease in tumor burden (45). Rapamycin blocks Wnt-mediated cell growth by interacting with mTOR, which is a central regulator of cell growth (46). Similarly, the antibiotic Streptonigrin was reported to block the complex formation of β-catenin/TCF (T-cell factor signaling) with DNA in human cell lines (47). In our study, the reduction of nuclear β-catenin following treatment with antimicrobial agents is likely due to bacterial killing, because, to our knowledge, no evidence indicates that amoxicillin or clarithromycin influence the Wnt/β-catenin signaling pathway. Of note, companion studies conducted by our group (J.I. Gilbreath et al., submitted for publication) have defined the microbiome of pseudomyxoma peritonei tumors from 11 patients and shown the ability to culture bacteria directly from pseudomyxoma peritonei tumor tissue. That study further indicated that antibiotic administration improves the survival of PMCA patients without pseudomyxoma peritonei observed in the lymph nodes when compared with untreated patients and historical data. Antibiotic treatment did not improve the survival of patients with lymph nodes positive for pseudomyxoma peritonei. Thus, treatment with antibiotics may be a beneficial therapy for pseudomyxoma peritonei patients with nonmetastatic disease.

We have not determined which mechanism is responsible for the reduction of nuclear β-catenin following antibiotic treatment or whether bacteria other than H. pylori contribute to abnormal β-catenin localization. It is plausible that the diminished β-catenin levels could be due to the loss of direct contact between tumor cells and bacteria or caused by a reduced inflammatory response to bacteria. In fact, DeNardo and colleagues propose that chronic inflammation could lead to Wnt/β-catenin activation without specific interactions between bacteria and epithelial cells (48). In this model, TNF-α produced by activated macrophages binds to TNF receptors on nearby epithelial cells, leading to AKT phosphorylation and the subsequent stabilization of β-catenin.

Recent studies have revealed the influence of several bacterial species on β-catenin expression and localization. H. pylori is present in the intercellular spaces, where the bacteria disrupt apical tight junctions as well as perturb molecular expression of β-catenin and other proteins of the lateral cell-to-cell membrane (49, 50). Salmonella activates the Wnt/β-catenin pathway via the secreted effector protein AvrA (21). Campylobacter rodentium, Bacteroides fragilis, and Chlamydia trachomatis also influence Wnt/β-catenin signaling (15, 22). Given the effect of bacteria on β-catenin signaling, which is known to contribute to the carcinogenic process, it is interesting to note that many common cancers occur in anatomical regions frequently exposed to bacteria, including cancers of the throat, lung, gastrointestinal tract, reproductive tract, and skin. Other locations, such as the breast, may seem to exist as sterile sites; however, bacteria can often gain entry, raising the possibility that individual bacterial species or a combination of different species could contribute to the carcinogenic process in multiple cancers. Thus, determining which bacterial species are involved in these processes could lead to targeted antimicrobial therapy and help to improve current methods for preventing and treating cancer.
Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Authors' Contributions

Conception and design: C. Semino-Mora, T.L. Testerman, C. Nieroda, D.S. Merrell, A. Dubois
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Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): C. Semino-Mora, H. Liu, K. Studeman, Y. Jia, C. Nieroda
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): C. Semino-Mora, T.L. Testerman, H. Liu, T.J. McAvoy, D.S. Merrell, A. Dubois
Writing, review, and/or revision of the manuscript: C. Semino-Mora, T.L. Testerman, J.M. Whitmire, T.J. McAvoy, C. Nieroda, A. Sardi, D.S. Merrell, A. Dubois
Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): H. Liu, T.J. McAvoy, I. Francis
Study supervision: A. Sardi, D.S. Merrell, A. Dubois

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During the writing of this article, Dr. A. Dubois passed away unexpectedly. Although ill for a lengthy time, he did not want others to be concerned and was silent about this fact. Throughout his illness, he worked diligently and passionately on the pseudomyxoma peritonei research. His wisdom, generosity, and expertise will be sorely missed by his colleagues and the research community. In addition, Dr. C. Semino-Mora passed away after the submission of the original manuscript. Despite a lengthy illness, she continued to contribute her abilities to several research projects. Her extensive skills and expertise were a tremendous asset that cannot be replaced. The authors thank Dr. D. McDaniel for his assistance with laser confocal imaging along with M. Sittig and M. Putman for their contributions to this project.

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5. Witkamp AJ, de Bree E, Van Goethem R, Zoetmulder FA. Rationale and expected. Although ill for a length of time, he did not want others to be concerned and was silent about this fact. Throughout his illness, he worked diligently and passionately on the pseudomyxoma peritonei research. His wisdom, generosity, and expertise will be sorely missed by his colleagues and the research community. In addition, Dr. C. Semino-Mora passed away after the submission of the original manuscript. Despite a lengthy illness, she continued to contribute her abilities to several research projects. Her extensive skills and expertise were a tremendous asset that cannot be replaced. The authors thank Dr. D. McDaniel for his assistance with laser confocal imaging along with M. Sittig and M. Putman for their contributions to this project.

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Antibiotic Treatment Decreases Microbial Burden Associated with Pseudomyxoma Peritonei and Affects β-Catenin Distribution

Cristina Semino-Mora, Traci L. Testerman, Hui Liu, et al.


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