Induction of experimental ulcerative colitis by *Fusobacterium varium* isolated from colonic mucosa of patients with ulcerative colitis

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Methods

**Isolation of mucosal bacteria**

Biopsy specimens were obtained with informed consent from the inflamed mucosa of 10 patients (mean age 36 (SD 11) years; seven men and three women). Patients were selected at random from 31 consecutive patients with active UC, diagnosed by endoscopic and pathological findings, and had no prior history of antibiotic use. Mucosal microorganisms were examined bacteriologically as described elsewhere. In brief, specimens were first incubated with imipenem (50 µg/ml saline) for one hour at 37°C. Serially diluted samples were spread on four agar plates for aerobic and eight agar plates for anaerobic culture. Isolated bacteria were examined by the disk diffusion test for imipenem sensitivity (minimal inhibitory concentration <4 µg/ml).

**In vitro toxicity tests**

Culture supernatants (pH 6.3–6.6) from all 42 isolates of 20 species were tested for toxicity to Vero cells. Vero cells were grown in Ham nutrient mixture F12 (Nissui Pharmaceutical Co, Tokyo, Japan) with 10% fetal calf serum and 50 mg/ml gentamicin. Vero monolayers were obtained by seeding 10^3 cells in each well 48 hours before use. Bacterial strains were incubated in ABCM broth (Eiken Chemicals, Tokyo, Japan) at 37°C for 72 hours. The density of cultured bacteria was estimated by counting the number of colonies per millilitre. Culture supernatant (25 µl) was added to each 100 µl well of
Vero cell cultures that had been grown in 96 well plates. Cultures were incubated at 37°C for 96 hours and examined for the proportion of cells with morphological changes. When a supernatant showed toxicity to Vero cells, the twice diluted supernatant with phosphate buffered saline (PBS) was retested for toxicity. Culture supernatant of E. coli O157:H7 EDL-931 was used as a positive control, and negative controls were PBS and ABCM broths.

**Polymerase chain reaction (PCR)**

Bacteria from one or two colonies of each cytotoxic strain were tested for verotoxin genes, as described elsewhere. Amplification was with the following primer sets: 5′-AGTTAAT GTGAGGCCGAA-3′ and 5′-GACTCTTCATCTGCG-3′ for verotoxin 1 (from nucleotides 289 to 1,099), and 5′-TTCGGTATCCTATTCCCG-3′ and 5′-GACTCTTCATCTGCG-3′ for verotoxin 2 (289 to 759) (Takara Shuzo, Ohtsu, Shiga, Japan). PCR conditions were three minutes at 94°C, 30 seconds at 55°C, and 30 seconds at 72°C for 25 cycles, and amplified DNA was analysed by submarine gel electrophoresis (1.5% agarose; 5 V/cm) and stained with ethidium bromide. PCR conditions were three minutes at 94°C, 30 seconds at 55°C, and 30 seconds at 72°C for 25 cycles, and amplified DNA was analysed by submarine gel electrophoresis (1.5% agarose; 5 V/cm) and stained with ethidium bromide. As a positive control, template DNA of E. coli O157:H7 EDL-931 was included.

**Identification of toxin size**

Culture supernatants of cytotoxic bacteria were concentrated 20-fold with Centriprep concentrators (molecular weight cut offs 100 000 to 3000; Amicon, Beverly, Massachusetts, USA) and with Diallo ultrafiltration membranes YC1 and YC05 (molecular weight cut offs 1000 and 500; Amicon). Dialysates were assayed for toxicity. For inactivation of heat unstable endotoxin, concentrates and dialysates were heated at 120°C for 15 minutes. Concentrates and dialysates were tested for protease sensitivity by incubation at 37°C for one hour, both with and without a mixture of pronase and trypsin (200 μg/ml each).

**Organic acid assay**

Supernatants of cytotoxic bacteria were assayed for organic acid concentrations. The aqueous phase was filtered through a cellulose acetate membrane (pores 0.20 μm; DISMIC-13 cp; Tokyo Roshi, Tokyo, Japan) and samples were examined by high performance liquid chromatography, as described elsewhere. Mean concentrations of organic acids in toxic culture supernatants were determined, and solutions of each organic acid were tested for toxicity. The cytotoxicity of organic acids in toxic culture supernatants was compared in dose-response experiments. The lowest mean concentration that killed >99% of cells after 96 hours of incubation was estimated by counting non-adherent cells under a microscope. Untreated Vero cells were used as controls. pH was measured in both organic acid treated and control wells of Vero cell cultures using a pH meter (PH5011A, Custom Co., Tokyo, Japan).

**In vivo toxicity test**

Four week old male CBA/J mice were given an enema of 32 mmol/l butyric acid (pH 3.2) under ether inhalation anaesthesia. The concentration was extrapolated from the mean concentration of n-butyr acid in separate culture supernatants of all five cytotoxic strains (all *Fusobacterium varium*).
after incubation for 72 hours at 37°C. Mice were treated with 1.0 ml of the butyric acid solution (n=8) or the supernatants (pH 6.3–6.6) from F varium cells grown to a concentration of 1×10⁹ colony forming units (CFU)/ml (n=9). Control mice were given an enema of 1.0 ml of 2 mmol/l HCl (n=8, pH 2.22), PBS (n=10), or ABCM broth (n=8). The anal verge was shut with cyanoacrylate and animals were killed under ether anaesthesia 24 hours later. Up to 3 cm of the rectum and colon from the anal verge were removed and fixed in 10% buffered formalin (pH 7.2). Longitudinal blocks were embedded and stained with haematoxylin and eosin (H&E). The remaining tissue was frozen in liquid nitrogen and cryostat sections were examined for apoptosis using terminal uridine DNA nick end labelling (TUNEL).

The modified standard scoring system was evaluated numerically in a blind fashion, according to the following scheme: 0, normal; 1, focal inflammatory cell infiltration including polymorphonuclear leucocytes; 2, gland loss with inflammatory cell infiltration or crypt abscesses; 3, mucosal ulceration (<1 mm long); and 4, multiple ulcerations or long mucosal ulceration (≥1 mm long). At least 2500 epithelial cells were counted in each section and the number of affected cells per 100 cells was expressed as the apoptotic index (%). For each mouse, one pathologist (IO), blind to the results of treatment, made an independent histological diagnosis.

**Table 2** Concentrations of organic acids in broth with and without Fusobacterium varium isolated from colonic mucosa of patients with ulcerative colitis

<table>
<thead>
<tr>
<th>Organic acid</th>
<th>Culture (n=5)</th>
<th>ABCM broth only (n=2)</th>
<th>Well of Vero cell culture†</th>
<th>Cytotoxicity to Vero cell</th>
<th>Lowest concentration for cytotoxicity† (pH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maleic acid</td>
<td>0.108 (0.011)</td>
<td>0.188 (0.019)</td>
<td>0.022 [7.87 (0.18)]</td>
<td>–</td>
<td>5.0 [5.30 (0.08)]</td>
</tr>
<tr>
<td>Succinic acid</td>
<td>7.51 (0.93)</td>
<td>1.04 (0.28)</td>
<td>1.50 [7.16 (0.11)]</td>
<td>–</td>
<td>6.5 [5.77 (0.08)]</td>
</tr>
<tr>
<td>Lactic acid</td>
<td>16.3 (5.90)</td>
<td>9.99 (1.23)</td>
<td>3.26 [7.27 (0.14)]</td>
<td>–</td>
<td>12 [6.24 (0.10)]</td>
</tr>
<tr>
<td>Formic acid</td>
<td>1.17 (0.37)</td>
<td>1.28 (0.05)</td>
<td>0.234 [7.84 (0.17)]</td>
<td>–</td>
<td>5.0 [7.03 (0.10)]</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>26.5 (3.5)</td>
<td>4.49 (0.22)</td>
<td>5.30 [6.93 (0.13)]</td>
<td>–</td>
<td>17 [5.02 (0.09)]</td>
</tr>
<tr>
<td>Propionic acid</td>
<td>7.13 (0.56)</td>
<td>ND</td>
<td>1.43 [7.52 (0.23)]</td>
<td>–</td>
<td>5.0 [7.02 (0.08)]</td>
</tr>
<tr>
<td>n-Butyric acid</td>
<td>32.1 (3.9)</td>
<td>ND</td>
<td>6.42 [6.90 (0.15)]</td>
<td>+</td>
<td>1.5 [7.65 (0.10)]</td>
</tr>
<tr>
<td>Total</td>
<td>90.8 (4.6)</td>
<td>17.0 (1.1)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Results are means (SD). †Fifthfold diluted concentration of organic acids in cultured broth with Fusobacterium varium. ND, not detected.

**RESULTS**

**In vitro toxicity of mucosal bacteria**

Table 1 lists the isolated bacterial species. All strains detected were susceptible to imipenem and the number of organisms cultured in ABCM broth at 37°C for 72 hours was 1–2×10⁹ CFU/ml. Culture supernatants of all five F varium strains were cytotoxic for Vero cells (fig 1). Twice diluted supernatants of all five F varium strains were also cytotoxic for Vero cells but supernatants diluted 1:4 were not cytotoxic. On the other hand, genes coding for verotoxin were not found in F varium.

**Statistical analysis**

Differences in pathological and apoptotic indices between groups given different enemas were evaluated by the Mann-Whitney U test with Bonferroni’s correction. Differences with p<0.05 were considered to be statistically significant.
Visual inspection showed mucosal erosions in the colorectum of mice treated with supernatants of *F. varium* culture supernatant or butyric acid enemas. The mean pathological index of mice treated with *F. varium* (3.3) or butyric acid (3.5) was higher than that of mice treated with HCl (p = 0.021 and 0.019), ABCM broth (both p < 0.001), or phosphate buffered saline (PBS) (both p < 0.001). Similarly, the mean apoptotic indices for mice treated with *F. varium* (24.0%) or butyric acid (20.8%) were higher than for HCl (p = 0.0045 and 0.012), ABCM broth (both p < 0.001), or PBS (both p < 0.001). The mean apoptotic index of mice treated with HCl (10.1%) was higher than that of ABCM broth or PBS (both p < 0.001). Values are mean (SD); statistical analyses were performed using the Mann-Whitney U test with Bonferroni’s correction.

Neither the supernatants from other species nor the cultivation broth were toxic (table 1). The culture supernatant of the *E. coli* positive control was toxic.

**Identification of verotoxin**

We tried to identify the toxic substance(s) from *F. varium*. Supernatants passed through a filter with a molecular weight cut off of 500 were treated with both heat and filtration of two *Bacteroides* species. As the mean concentration of butyric acid produced culture conditions of pH 3.20 in the supernatants, but the pH changed to pH 6.90 in wells that were cytotoxic for Vero cells, cytotoxicity does not appear to be related to pH.

Acetic acid, propionic acid, and butyric acid are produced by anaerobic bacteria in the colon and are rapidly absorbed to provide energy for the colorectal epithelium. However, butyric acid, propionate, and acetate also induce apoptosis in a number of colorectal tumour cell lines. Butyrate has the greatest effect. Therefore, toxicity towards Vero cells may involve induction of apoptosis by butyric acid produced by bacteria. The higher apoptotic indices in mice treated with butyric acid or supernatants of cultured *F. varium*, compared with controls, is in agreement with results in patients with active UC.

Our data do not support the possibility that increased luminal acidity causes epithelial damage in our model. Specifically, mucosal erosions were observed in mice treated with pH 6.3–6.6 supernatants of *F. varium* but not in control mice treated with HCl (pH 2.22). Our results showed that apoptotic indices in the mucosa treated with *F. varium* and butyric acid were elevated compared with controls treated with HCl, ABCM broth, or PBS. Therefore, it is more likely that butyric acid and butyric acid rich supernatants of cultured *F. varium* in the enemas induced mucosal cell apoptosis that caused the ulceration, rather than acidity.

Defective butyrate metabolism may be involved in the pathogenesis of UC. Colonocytes from patients with UC oxidise less butyric acid than cells from controls without mucosal abnormalities. It is possible that the high concentrations of butyric acid and butyric acid rich supernatants of cultured *F. varium* in the enemas administered to mice were in excess of that which could be metabolised by the colonic epithelium, thus inducing mucosal cell apoptosis and causing ulceration. Our finding that butyric acid is associated with ulceration is seemingly in contradiction to reports that enemas of sodium butyrate have been used successfully to treat UC. However, in a controlled trial, enemas of sodium butyrate were not effective in the treatment of UC, and the substance used in the reported studies is not the same as the butyric acid that was used in our experiments.

Our immunochemical analysis of biopsy specimens from active UC cases suggests that *F. varium* invades the mucus and mucosa and lives in crypts. Production of butyric acid within these crypts would be expected to impact directly on epithelial cells. Similarly, *H. pylori* can be found in the gastric mucosa of most patients with chronic gastritis or peptic ulcers, inhibiting the mucous layer of the epithelium or invading the epithelium itself.
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