Prebiotic Inulin Enriched with Oligofructose in Combination with the Probiotics Lactobacillus rhamnosus and Bifidobacterium lactis Modulates Intestinal Immune Functions in Rats

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ABSTRACT Probiotics (PRO) modulate systemic immunity in animals and humans. In contrast, the effects of prebiotics (PRE) on systemic and intestinal immunity have not been investigated. Whether the combined application of PRO and PRE [symbiotics (SYN)] has synergistic or additive effects is presently unknown. Therefore, PRO (Lactobacillus rhamnosus GG and Bifidobacterium lactis Bb12), PRE (inulin enriched with oligofructose), and SYN (combination of PRO and PRE) were fed to F344 rats for 4 wk as supplements to a high fat diet. Functions of immune cells isolated from peripheral blood mononuclear cells (PBMC), spleen, mesenterial lymph nodes and Peyer’s patches (PP) were investigated. The SYN supplement increased secretory immunoglobulin A (sIgA) production in the ileum compared with controls fed the high fat diet alone (P < 0.05), compared with rats fed PRO. The PRE supplement enhanced the production of interleukin-10 (P < 0.05) in PP as well as the production of sIgA in the cecum (P < 0.05), compared with controls. The PRE supplement modestly affected immune functions, whereas systemic immunomodulatory effects were observed in rats fed SYN. The PRE supplement primarily acted at the level of the gut-associated lymphoid tissue. The combined application of PRO and PRE has different effects from those of the individual supplements, but does not simply result in additive or synergistic effects. J. Nutr. 134: 153–156, 2004.

KEY WORDS: • Immune sytem • gut • probiotic • prebiotic • symbiotic • rat

Several recent reviews summarized the available experimental evidence for the immunomodulatory effects of probiotics (PRO)4. Although experimental and human studies clearly show that PRO affect host resistance to intestinal infections as well as a number of immune cell functions, the results of these studies vary greatly. In addition, the underlying immunological mechanisms of PRO are generally not well defined (3,4). The gut-associated lymphoid tissue (GALT) is increasingly recognized as a crucial component of immune response (5). Although many studies have focused on the systemic immunological effects of PRO, few data are available regarding systemic immunological effects and local immunological effects in the gut in the same animal (6). Therefore, studies investigating the immunomodulatory potential of PRO, including their effects at the GALT level, are needed.

At present, few studies have investigated the direct effects of prebiotics (PRE) on the immune system (7). Whether PRE modulate the immune response directly or indirectly, by affecting the composition of the intestinal flora and thus affecting the GALT, or by producing SCFA, is presently unknown.

Our study investigated the effects of PRO, PRE and their combined application [symbiotics (SYN)] at the systemic level and at the GALT level. We hypothesized that PRO and PRE, alone or in combination, would modify immune responses in the GALT, enhancing cytokine production and other immune cell functions. Therefore, we fed F344 rats consuming a high fat, low fiber control diet a daily supplement consisting of two probiotic strains (Lactobacillus rhamnosus GG and Bifidobacterium lactis Bb12), an inulin-based prebiotic enriched with oligofructose or the combination of PRO and PRE (SYN) for a period of 4 wk. We decided to use two probiotic strains because others have suggested that a mixture of PRO may have a greater effect on the intestine than the individual strains (8,9). We assessed a broad spectrum of immune functions with cells isolated from peripheral blood mononuclear cells (PBMC) and the spleen as well as from the GALT. We used a Western-style high fat, low fiber diet instead of a standard rat diet as the control diet to make the study conditions more comparable to the situation of humans in Western countries consuming PRO and/or PRE.

MATERIALS AND METHODS

Animals. The State Veterinary Office granted permission for the rat studies, and the experiments complied with its guidelines for the care and use of laboratory animals. Male Fischer 344/NHsd rats (Harlan Winkelmann, Borchen, Germany) aged 12 to 13 wk were fed a standard lab diet (Altromin, Lage, Germany) for 1 wk, and all rats were then fed the control diet for 1 wk.

Diets. Dietary components were purchased from Piccioni (Gessate, Milan, Italy). RaftiloseR Synergy1 was provided by Orafti (Tienen, Belgium). This PRE is an oligofructose-enriched inulin,
comprised of a 1:1 mixture of long- and short-chain fractions of inulin, a β(2→1)-fructan extracted from chicory roots (Cichorium intybus). L. rhamnosus GG (LGG) and B. lactis Bb12 (Bb12) were provided by Valio (Helsinki, Finland) and purchased from Chr. Hansen (Hørsholm, Denmark), respectively. They were supplied as freeze-dried powder in sealed packets containing ~6 × 10^10 colony-forming units (CFU)/g (LGG) and ~3 × 10^11 CFU/g (Bb12), respectively. The bacteria were stored at a temperature of ~20°C until used. The dietary concentration of LGG and Bb12 was evaluated as described elsewhere (10).

Rats (n = 80) were allocated to four experimental groups (n = 20). The control group was fed a high fat (HF) diet based on the AIN76 diet (11), modified to contain a high level of fat (231 g corn oil/kg) and a low level of cellulose (20 g/kg) to compare with the diet typical of Western humans at high risk of colon cancer (10). The sources of carbohydrates in this diet were sucrose (361 g/kg) and maltodextrin (100 g/kg). The PRO group was fed an HF diet supplemented with LGG and Bb12 to provide ~5 × 10^11 CFU of each strain per kg of diet. The PRE group was fed an HF diet with the maltodextrins replaced by 100 g/kg of Raftilose Synergy1. The SYN for 4 wk did not affect feed intake (15.0 ± 1.05 g/d), and ideal contents (10 mg/rat) were mixed with 1 mL of a solution (10 g/L) of bovine serum albumin (BSA; Sigma-Aldrich) in PBS and incubated for 10 min at room temperature. Samples were centrifuged (4000 × g, 30 min, 20°C) and supernatants were collected and stored at ~20°C until assayed. Maxisorb 96-well microtiter plates (NUNC, Roskilde, Denmark) were coated with 100 μL of a rabbit anti-secretory component antibody (Bethyl Laboratories, Montgomery, AL) diluted 1:1000 with a solution (50 mL) of Tween 20 (Sigma) in PBS and incubated overnight at 4°C. After blocking with 100 μL of BSA (40 g/L) in the Tween solution for 1 h and washing, 100-μL titers of the samples were applied. After incubation for 2 h, 100 μL of hors eradish peroxidase-conjugated goat monoclonal anti-rat IgA (Bethyl Laboratories) diluted 1:500 with the Tween-BSA solution was added, and the plates were then incubated for 2 h. A peroxidase substrate, 100 μL of tetrathylbenzidine (Kirkegaard & Perry Laboratories, Gaithersburg, MD) was then added, and the plates were incubated for 30 min in the dark. The enzyme reaction was stopped with 100 μL of 1 mol/L H_2PO_4. The relative amount of secretory immunoglobulin A (sIgA) was quantified by measuring the absorbance at 450 nm.

RESULTS

Supplementation of the control diet with PRO, PRE and SYN for 4 wk did not affect feed intake (15.0 ± 1.05 g/d), weight gain (46 ± 11 g), and final body weight (370 ± 21 g). The intake of LGG was ~7.3 ± 0.5 × 10^10 CFU/d, and intake of Bb12 was 7.6 ± 0.6 × 10^10 CFU/d.

No significant differences in CD4^+ and CD8^+ T-lymphocytes were observed among the treatment groups in any of the tissues studied (data not shown). In the blood the CD4/CD8 ratio tended to be greater (P = 0.08) in rats treated with PRO or SYN than in the control or PRE groups (control, 1.80 ± 0.22; PRE, 1.81 ± 0.16; PRO, 1.95 ± 0.35; SYN, 1.95 ± 0.21).

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The intestine contents of the ileum and cecum were collected and stored at ~3°C until assayed.

Fluorescence staining of lymphocyte subpopulations. The expression of cell surface markers on the immune cells of blood, spleen and mesenteric lymph nodes (MLN) was investigated by immunofluorescence as previously described (12). Phycoerythrin-conjugated mouse anti-CD monoclonal antibodies to CD4 (Caltag, Hamburg, Germany) and fluorescein-conjugated mouse anti-CD monoclonal antibodies to CD8 (Caltag) with appropriate isotype controls (Caltag) were used. Samples were analyzed with a FACSCalibur flow cytometer (BD Biosciences, Heidelberg, Germany).

Phagocytosis. The phagocytic capacity of the immune cells of the blood and the spleen was assessed with a flow cytometric method as previously described (13).

Oxidative burst. Whole blood (100 μL) was cooled on ice to 0°C. Tubes were incubated with 20 μL PBS (control) or 20 μL phorbol myristate 13-acetate (8.1 μmol/L; Sigma-Aldrich, Deisenhofen, Germany), as a high stimulus for 10 min at 37°C. Dihydrodolamide 123 (1.7 μL, 29 mmol/L; Molecular Probes, Leiden, Netherlands) was added and samples were incubated for 15 min at 37°C. Erythrocytes were lysed with 2 mL 1× lysing solution. After centrifugation (250 × g, 4°C, 5 min), cells were washed with 3 mL PBS. The cells were resuspended in 300 μL propidium iodide (0.75 μmol/L; Sigma-Aldrich) and incubated for 10 min on ice. Samples were analyzed within 30 min with the flow cytometer.

Cytotoxicity of natural killer (NK) cells. The natural killer (NK) cell activity of the immune cells of the blood, spleen, MLN and PP was assessed with a flow cytometric method as previously described (14), using target cells from the mouse Moloney leukemia cell line YAC-1.

Lymphocyte proliferation. The ex vivo proliferative responsiveness of lymphocytes isolated from the spleen, MLN (each 5 × 10^6 cells/L) and PP (7 × 10^6 cells/L) to the mitogen concanavalin A (ConA; 1 μg/mL; Sigma-Aldrich, Deisenhofen, Germany) for 72 h at 37°C, 5% CO_2 and 95% humidity was determined by ELISA, using a commercial proliferation kit (Cell Proliferation ELISA kit; Roche Diagnostics, Mannheim, Germany).

Cytokines. Splenocytes (100 μL; 1 × 10^6 cells/L IFN-γ and 5 × 10^6 cells/L IL-10), MLN (100 μL; 1 × 10^6 cells/L IFN-γ and 5 × 10^6 cells/L IL-10) and PP (100 μL; 5 × 10^6 cells/L IFN-γ and 5 × 10^6 cells/L IL-10) were stimulated by 100 μL of Con A (5 mg/L) for 24 h at 37°C, 5% CO_2, and 95% humidity. Levels of IFN-γ and IL-10 in the supernatants were measured with OptEIA commercial ELISA kits (BD Pharmingen, Heidelberg, Germany), following the manufacturers’ instructions.

Secretory immunoglobulin A (sIgA). Fresh caecal (140 mg/rat) and ileal contents (10 mg/rat) were mixed with 1 mL of a solution (10 g/L) of bovine serum albumin (BSA; Sigma-Aldrich) in PBS and incubated for 10 min at room temperature. Samples were centrifuged (4000 × g, 30 min, 20°C) and supernatants were collected and stored at ~20°C until assayed. Maxisorb 96-well microtiter plates (NUNC, Roskilde, Denmark) were coated with 100 μL of a rabbit anti-secretory component antibody (Bethyl Laboratories, Montgomery, AL) diluted 1:1000 with a solution (50 mL) of Tween 20 (Sigma) in PBS and incubated overnight at 4°C. After blocking with 100 μL of BSA (40 g/L) in the Tween solution for 1 h and washing, 100-μL titers of the samples were applied. After incubation for 2 h, 100 μL of horseradish peroxidase-conjugated goat monoclonal anti-rat IgA (Bethyl Laboratories) diluted 1:500 with the Tween-BSA solution was added, and the plates were then incubated for 2 h. A peroxidase substrate, 100 μL of tetrathylbenzidine (Kirkegaard & Perry Laboratories, Gaithersburg, MD) was then added, and the plates were incubated for 30 min in the dark. The enzyme reaction was stopped with 100 μL of 1 mol/L H_2PO_4. The relative amount of secretory immunoglobulin A (sIgA) was quantified by measuring the absorbance at 450 nm.
The SYN treatment enhanced the slgA concentration in the ileum \((P < 0.05)\), and the PRE treatment increased it in the cecum \((P < 0.05; \text{Table 3})\), relative to the control group.

**DISCUSSION**

The objectives of the present study were to investigate whether the effects of PRO and PRE on the immune system vary among different immune compartments and whether SYN has a greater effect than that obtained with PRO or PRE supplementation alone. The results demonstrate that PBMC and PP are the primary tissues that are specifically affected by PRE. In addition, although PRE supplementation alone induced significant immunomodulation in the intestine, PRO supplementation was primarily effective when provided as a component of SYN.

We used a high fat, low-fiber diet instead of a standard rat diet because it more closely resembles the dietary conditions of Western humans consuming PRO and/or PRE. The fat content of the diet affects immune functions such as NK cell activity (15). Therefore, the potential immunomodulatory effects of PRO and PRE may become more obvious in subjects fed such a diet.

Overall, the treatments did not affect the subpopulations of lymphocytes in the blood, spleen and MLN. However, the PRO and SYN treatments tended to increase the CD4/CD8 ratio in the blood. This suggests that LGG + Bb12 treatment modulates the composition of circulating lymphocytes in the periphery. In another study with rats, consuming yogurt \((Lactobacillus bulgaricus\) and \(Streptococcus thermophilus\)) for 4 wk did not affect lymphocyte subpopulations in the PBMC and spleen when compared with unfermented milk (6). In mice, consuming lactic acid bacteria (LAB) for 4 wk did not affect the percentages of \(CD4^+\) and \(CD8^+\) cells in the blood (16).

**TABLE 2**

<table>
<thead>
<tr>
<th>Cytokine</th>
<th>Control</th>
<th>PRO</th>
<th>PRE</th>
<th>SYN</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu g/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IFN</td>
<td>2.7 ± 0.8</td>
<td>2.7 ± 1.0</td>
<td>3.6 ± 2.0</td>
<td>2.9 ± 1.2</td>
</tr>
<tr>
<td>IL-10</td>
<td>0.31 ± 0.13a</td>
<td>0.37 ± 0.19ab</td>
<td>0.56 ± 0.38b</td>
<td>0.46 ± 0.29ab</td>
</tr>
</tbody>
</table>

1 Values are means \(\pm\) SD, \(n = 20\). Means in a row without a common letter differ, \(P < 0.05\).

2 Lymphocytes were stimulated with 5 mg/L concanavalin A (ConA) and cultivated for 24 h.

Altogether these data suggest that PRO and PRE have only minor effects on the composition of \(T\) cell subsets in different immune compartments. In contrast to a number of animal and human studies (17), the present study found that PRO treatment did not stimulate neutrophil and monocyte phagocytosis. A study with humans also found that \(Lactobacillus casei\) Shirota supplementation for 4 wk did not affect phagocytosis in healthy adults (18). Because the subjects of that study also consumed a high fat diet comparable to the one used in the present study with rats, the basic diet might be at least partly responsible for the observed differences. The reason for the significant reduction of the oxidative burst activity in the SYN group is unknown.

In the present study, lymphocytes from the blood, spleen and GALT, including PP and MLN, exerted an NK-like cytotoxic effect (based on their capacity to lyse the YAC-1 target cell line). Because no earlier study reported NK cell activity in rat PP, we used pentoxifylline (PTX), a suppressor of NK cell activity (19), to suppress NK cell activity in the spleen and PP. The PTX suppressed NK cell activity in both tissues (data not shown).

The PRO and SYN treatments tended to enhance NK cell activity only in blood. This suggests that LGG + Bb12 supplementation may have caused this increase. Studies in humans have demonstrated that \(L. rhamnosus\) (strain HNO01) and \(B. lactis\) (strain HN019) supplementation upregulate PBMC NK cell cytotoxicity (17), although the overall nutritional status of the study subjects also modulated the effect of this PRO treatment (20). These data support the observations of the present study with rats. Supplementation with \(B. lactis\) in oligosaccharide-enriched milk caused higher NK cell cytotoxicity in humans than the PRO treatment without the oligosaccharide (21).

The capacity of lymphocytes isolated from the spleen, MLN and PP to proliferate following mitogen activation was not affected by the dietary treatments. This conflicts with animal studies on strains of LAB which found that consuming yogurt \((\sim 1.4 \times 10^8\) bacteria/d) or pure bacteria increased the proliferative responsiveness of lymphocytes to ConA (6,16). Again, differences in the composition of the control diets may explain the differing outcomes of these studies.

The PRE treatment significantly stimulated IL-10 production by PP cells. In PP, IFN and IL-10 are primarily produced by T-helper1 lymphocytes (IFN) and by T-helper2/T-regulatory lymphocytes and dendritic cells (IL-10). The strong correlation between the level of production of the two cytokines \((r = 0.90, P < 0.0001)\) suggests that the PRE treatment simultaneously activated different T-lymphocyte subpopulations and/or dendritic cells. The PRE treatment did not affect splenocytes or mesenteric lymphocytes, which constitutively

**TABLE 3**

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Control</th>
<th>PRO</th>
<th>PRE</th>
<th>SYN</th>
</tr>
</thead>
<tbody>
<tr>
<td>OD450</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ileum</td>
<td>0.78 ± 0.36a</td>
<td>0.92 ± 0.41ab</td>
<td>1.09 ± 0.62ab</td>
<td>1.30 ± 0.75b</td>
</tr>
<tr>
<td>Caecum</td>
<td>0.66 ± 0.42a</td>
<td>0.88 ± 0.59ab</td>
<td>1.15 ± 0.77b</td>
<td>0.72 ± 0.31ab</td>
</tr>
</tbody>
</table>

1 Values are means \(\pm\) SD, \(n = 20\). Means in a row without a common letter differ, \(P < 0.05\).
express lower levels of multiple cytokine transcripts than PP (22). In contrast to the strong effects of PRE on PP cytokine production, the combined treatment with PRO and PRE abrogated this effect. Because PRE did not affect the proliferative responsiveness of PP to the mitogen ConA, the increase in cytokine production indicates that PRE and/or its metabolites may interfere specifically with the regulatory processes of cytokine production. A recent study with mice also reported that consuming fructooligosaccharide enhanced IFN and IL-10 production by PP cells (23), confirming the results of the present study. Consuming the probiotic raffinose further increased IL-12 production of PP (24), which enhances IFN production in PP (25). However, feeding mice yogurt LAB (L. bulgaricus, S. thermophilus) had no effect on basal IFN mRNA expression in PP (26). In another study, feeding mice L. rhamnosus for 4 wk significantly increased IFN production by splenocytes, but B. lactis had no effect (18). Because we used both LAB strains in combination, this may have impeded enhanced IFN production by splenocytes in the present study.

Treatment with SYN (ileum) and PRE (cecum) increased concentrations of total sIgA in rats, whereas PRO alone had no effect. The availability of PRE in the ileum may have supported the growth of the supplemented PRO and consequently stimulated sIgA synthesis. In contrast, in the cecum there is a large quantity of endogenous microorganisms; PRE supported the growth of these bacteria, which also stimulated sIgA production. However, in rats treated with SYN, the PRE may have been metabolized in the ileum and therefore could not further support bacterial growth in the cecum. Our results are in line with those of a recent study that found that feeding mice fructooligosaccharides increased fecal IgA concentration (23). The mechanism of this sIgA-enhancing effect is unknown. The IFN stimulates expression of the secretory component of IgA by epithelial cells (27). However, we found no correlation between changes in IFN production by PP and caecal sIgA concentration with the PRE treatment (data not shown). This argues against a potential role of IFN.

In conclusion, PBMC are sensitive (CD4+, oxidative burst, NK) to PRO and SYN treatment, whereas PP are primarily sensitive to PRE treatment (cytokine and sIgA production). The spleen and MLN were not affected by any of the treatments. The present data suggest that PRO and PRE act via different mechanisms. Because we used a high fat, low dietary fiber diet rather than the standard low fat diet used by most other studies, our results may be more relevant to the situation of humans consuming PRO or PRE in Western-style diets.

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LITERATURE CITED