Differential cytokine response from dendritic cells to commensal and pathogenic bacteria in different lymphoid compartments in humans

Liam O’Mahony,1 Louise O’Callaghan,1 Jane McCarthy,1 David Shilling,2 Paul Scully,1 Shomik Sibartie,1 Eamon Kavanagh,2 William O. Kirwan,2 Henry Paul Redmond,2 John Kevin Collins,1 and Fergus Shanahan1

1Alimentary Pharmabiotic Centre and 2Department of Surgery, University College Cork, National University of Ireland, Cork, Ireland

Submitted 14 March 2005; accepted in final form 9 November 2005

O’Mahony, Liam, Louise O’Callaghan, Jane McCarthy, David Shilling, Paul Scully, Shomik Sibartie, Eamon Kavanagh, William O. Kirwan, Henry Paul Redmond, John Kevin Collins, and Fergus Shanahan. Differential cytokine response from dendritic cells to commensal and pathogenic bacteria in different lymphoid compartments in humans. Am J Physiol Gastrointest Liver Physiol 290: G839–G845, 2006. First published November 17, 2005; doi:10.1152/ajpgi.00112.2005.—Resident host microflora condition and prime the immune system. However, systemic and mucosal immune responses to bacteria may be divergent. Our aim was to compare, in vitro, cytokine production by human mononuclear and dendritic cells (DCs) from mesenteric lymph nodes (MLNs) and peripheral blood mononuclear cells (PBMCs) to defined microbial stimuli. Mononuclear cells and DCs isolated from the MLN (n = 10) and peripheral blood (n = 12) of patients with active colitis were incubated in vitro with the probiotic bacteria Lactobacillus salivarius UCC118 or Bifidobacterium infantis 35624 or the pathogenic organism Salmonella typhimurium UK1. Interleukin (IL)-12, tumor necrosis factor (TNF)-α, transforming growth factor (TGF)-β, and IL-10 cytokine levels were quantified by ELISA. PBMCs and PBMC-derived DCs secreted TNF-α in response to the Lactobacillus, Bifidobacteria, and Salmonella strains, whereas MLN cells and MLN-derived DCs secreted TNF-α only in response to Salmonella challenge. Cells from the systemic compartment secreted IL-12 after coincubation with Salmonella or Lactobacilli, whereas MLN-derived cells produced IL-12 only in response to Salmonella. PBMCs secreted IL-10 in response to the Bifidobacterium strain but not in response to the Lactobacillus or Salmonella strain. However, MLN cells secreted IL-10 in response to Bifidobacteria and Lactobacilli but not in response to Salmonella. In conclusion, commensal bacteria induced regulatory cytokine production by MLN cells, whereas pathogenic bacteria induce T cell helper 1-polarizing cytokines. Commensal-pathogen divergence in cytokine responses is more marked in cells isolated from the mucosal immune system compared with PBMCs.

mucosa; inflammation

STUDY POPULATION. This study was approved by the Ethics Committee of Cork University Hospital, and informed consent was obtained from all volunteers. The study population involved patients with IBD undergoing colectomy or small bowel resection. MLNs were obtained from 10 patients with active IBD (n = 10; age range 19–41 yr (mean 32.2 yr), 3 women and 7 men; 5 patients with Crohn’s disease (CD) and 5 patients with ulcerative colitis (UC)). All patients were prescribed and taking systemic steroids (5’-aminosalicylic acid). All patients required surgical section because of progressive disease and failure to respond to steroids. Peripheral blood mononuclear cells (PBMCs) were obtained from patients with active IBD (n = 12). The age range was 20–51 yr (mean 28 yr). Five women and seven men were studied; five patients with CD and seven patients with UC. None of the MLN and PBMC donors were the same subject.

MLN cell isolation. MLNs were selected for this study with careful regard to their anatomic location relative to areas of inflammation in

http://www.ajpgi.org
0193-1857/06 $8.00 Copyright © 2006 the American Physiological Society G839

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
the bowel. MLNs selected directly drained an inflamed area of the bowel. From three patients within this study population, it was possible to obtain MLN-draining segments of inflamed and noninflamed bowel. Single cell suspensions were generated from MLNs by gentle extrusion of the tissue through a 180-μm mesh wire screen. Cells were washed and resuspended in DMEM containing 10% fetal calf serum (FCS; Invitrogen; Paisley, UK). Mononuclear cells were isolated by Ficoll-Hypaque density centrifugation (3) and resuspended at 1 × 10^6 cells/ml in complete media-DMEM containing 25 mM glucose, 10% FCS, 1% nonessential amino acids, 50 U/ml penicillin, and 50 μg/ml streptomycin (Invitrogen). These mononuclear cells are termed MLN cells (MLNCs).

**PBMC isolation.** Peripheral blood was taken directly into sterile EDTA-containing vacutainers. Mononuclear cells were isolated from blood by Ficoll-Hypaque density gradient centrifugation. After a washing step, PBMCs were resuspended in complete media at 1 × 10^6 cells/ml.

**DC isolation.** DCs from the MLN and peripheral blood were isolated using identical procedures. Cells were resuspended at 5 × 10^7 cells/ml in PBS (without Ca^2+ or Mg^2+) with 4% FCS. For optimal recovery of DCs, 1 mM EDTA was added to all media, and cell suspensions were blocked with anti-CD32 antibodies (StemCell; Meylan, France). DCs were isolated from this cell suspension, according to the manufacturer’s protocol, using a DC negative isolation kit (StemSep depletion cocktail, StemCell). DCs were resuspended in Stemspan serum-free media (StemCell) at 1 × 10^6 cells/ml. Viability, determined by trypan blue exclusion, was consistently ≥98%. The purity of DC preparations was assessed using flow cytometry. Cells that were human leukocyte antigen (HLA)-DR positive and CD3/CD14/CD16/CD19/CD20/CD56 negative were termed DCs. All antibodies were obtained from BD Biosciences (Oxford, UK).

**Bacterial strains.** We (5) have previously reported the selection criteria for isolation of *Lactobacillus salivarius* UCC118 and *Bifidobacterium infantis* 35624. *L. salivarius* and *B. infantis* were routinely cultured anaerobically for 24–48 h in deMann, Rogosa, and Sharpe medium (MRS; Oxoid; Basingstoke, UK) and MRS supplemented with 0.05% cysteine (Sigma; Dublin, Ireland), respectively. *Salmonella typhimurium* UK1 was cultured aerobically for 18–24 h in tryptic soya broth (Oxoid). Bacterial cultures were harvested by centrifugation (3,000 g × 15 min), washed with PBS, and subsequently diluted to final cell densities of 1 × 10^7, 1 × 10^5, and 1 × 10^3 colony-forming units (cfu/ml) in DMEM.

**In vitro cell stimulations.** All cells were seeded in 24-well tissue culture plates (Costar; Schiphol-Rijk, Netherlands) at 1 × 10^6 cells/ml. MLNCs were stimulated for 72 h with *L. salivarius*, *B. infantis*, or...
S. typhimurium at three different bacterial concentrations: $1 \times 10^7$, $1 \times 10^8$, and $1 \times 10^9$ CFU. Because $1 \times 10^7$ CFU/ml bacteria resulted in significant stimulation of cytokine production, this bacterial concentration was used in subsequent experiments. MLNCs isolated from the noninflamed bowel and PBMCs were stimulated for 72 h with these bacteria at $1 \times 10^7$ CFU. MLN-derived and peripheral blood-derived DCs were stimulated with L. salivarius, B. infantis, or S. typhimurium. MLNC and PBMC cultures remained viable over the 72-h culture period (>95% viable at 72 h). DC viability decreased rapidly after a 24-h incubation, so all DC stimulations were terminated at 24 h (mean viability at 24 h >94%; mean viability at 72 h = 31%). Nonstimulated cells were present to assess spontaneous levels of cytokine secretion. Plates were incubated in a 5% CO2 and 37°C humidified atmosphere, after which supernatants were harvested for cytokine analysis. Cytokine production was measured, according to the manufacturer’s instructions, using commercially available ELISA kits (R&D Systems; Abington, UK). Cytokines measured included transforming growth factor (TGF)-β, interleukin (IL)-12 p40, IL-10, and lymphotoxin (LT)-β.

Intracellular cytokine staining. After stimulation of PBMCs with L. salivarius, B. infantis, or S. typhimurium, cells were examined by flow cytometry for intracellular cytokine expression. PBMC incubations were performed for 3, 6, and 12 h in the presence of Golgistop (BD BioSciences). Cells were stained with FITC-conjugated anti-CD3 antibodies for the identification of T cells, whereas DCs were identified as being CD3/CD14/CD16/CD19/CD20/CDS6 negative (FITC conjugated) and Cy5-HLA-DR positive. Cells were fixed and permeabilized using a Cytofix/Cytoperm kit (BD BioSciences) followed by coincubation with phycoerythrin-conjugated anti-IL-10 or anti-TNF-α antibodies. All antibodies were obtained from BD BioSciences. Flow cytometric analysis of the frequency of cytokine-positive cells was performed using a BD FacsCalibur and Cell Quest Pro software.

Statistical analysis. Results were analyzed using ANOVA. Values are illustrated as means ± SE. Statistically significant differences in cytokine production between nonstimulated cells (control) and cells stimulated with bacteria were accepted at $P < 0.05$.

**RESULTS**

Divergent immune responses of MLNCs to commensal and pathogenic bacteria. Strain-strain divergence in cytokine responses (i.e., commensal bacteria vs. pathogenic bacteria) was observed in MLNC-draining inflamed bowels (Fig. 1). L. salivarius and B. infantis induced IL-10 production by MLNCs at the highest bacterial dose ($10^7$ CFU). B. infantis also significantly induced TGF-β production, whereas L. salivarius induced TGF-β production did not reach statistical significance. L. salivarius and B. infantis did not induce TNF-α or IL-12. In contrast, S. typhimurium significantly induced IL-12 and TNF-α production by MLNCs but did not induce IL-10 or TGF-β.

To confirm that results were not skewed by the presence of inflammation in the resected specimens, MLNCs were isolated from two different drainage fields (from inflamed and noninflamed segments), which were available in three patients with restricted disease distribution. The patterns of response of MLNCs to commensals and pathogens were similar irrespective of whether they were from sites draining inflamed or noninflamed segments of bowel (Fig. 2). Thus the Lactobacillus and Bifidobacterium strains induced IL-10 and TGF-β production, whereas the Salmonella strain induced IL-12 and TNF-α production. However, whereas the cytokine pattern was similar between MLNCs from both sites, the quantity of S. typhimurium-stimulated IL-12 and TNF-α produced by the MLNC-draining inflamed bowel was greater than the levels produced by the MLNC-draining noninflamed bowel.

Comparison between MLNC and PBMC cytokine responses. The cytokine response of cells derived from the mucosal immune compartment to commensal bacteria was not reflected in the response of cells derived from the systemic compartment (Fig. 3). Whereas L. salivarius significantly induced IL-12 and...
Intracellular cytokine staining. In stimulated PBMC cultures, both T cells and DCs secreted IL-10 and TNF-α in response to coinubcation with each of the bacterial strains examined (Fig. 4). However, it is evident from these histograms that a greater percentage of the DC population (HLA-DR positive) was manufacturing cytokine compared with T cells within the same cultures. This suggests that DCs are responsible for the bulk of cytokines released into culture supernatants and measured using ELISA.

**DC cytokine responses to microbial challenge.** Isolated DC preparations were consistently >90% HLA-DR positive and CD3/CD14/CD16/CD19/CD20/CD56 negative (mean = 93.2 ± 2.9%). *L. salivarius* induced IL-10, TNF-α, and IL-12 secretion by peripheral blood-derived DCs but only induced IL-10 secretion from MLN-derived DCs (Fig. 5). *B. infantis* induced IL-10 and TNF-α but not IL-12 production by peripheral blood-derived DCs. *B. infantis* stimulated the production of IL-10 alone by MLN-derived DCs. *S. typhimurium* significantly induced IL-12 and TNF-α production by both MLN- and peripheral blood-derived DCs but only induced IL-10 secretion from PBMC-derived DCs. It is important to note that the absolute levels of cytokines released from DCs were substantially less than those released from mononuclear cell populations. This may reflect the different culture periods for DCs (24 h) and mononuclear populations (72 h) but also suggests that individual DC subpopulations require cooperation with other mononuclear cells to achieve the optimal response to bacterial challenge.

**Fig. 3. MLNC and peripheral blood mononuclear cell (PBMC) cytokine profiles.** Bacteria-induced cytokine production by MLNCs (n = 10) and PBMCs (n = 12) were divergent. *L. salivarius* induced IL-12 and TNF-α production by PBMCs, which were not induced in MLNCs. In addition, *L. salivarius* did not induce IL-10 production by PBMCs. *B. infantis* induced TNF-α production by PBMCs, which was not induced in MLNCs. *S. typhimurium* induced a similar cytokine profile from both MLNCs and PBMCs. Top: IL-12; middle: TNF-α; bottom: IL-10. Results are expressed as mean cytokine levels ± SE after stimulation with 0 (nonstimulated) or 1 × 10⁷ bacterial cells. *Significant difference between nonstimulated cells to cells stimulated with bacteria (P ≤ 0.05).
field of gastrointestinal tumors are subject not only to the immunosuppressive effects of occult micrometastases that are undetected by conventional histology but are also exposed to immunosuppressive factors from the primary tumor. However, the divergent results between the mesenteric and peripheral lymphoid compartments were not disease related because the samples from both sites were taken from patients with active disease. More importantly, we took advantage of the availability of lymph node-draining inflamed and noninflamed segments of colonic mucosa in the case of three individuals undergoing colectomy for subtotal colonic involvement with UC. The results showed that the patterns of cytokine responses to the different microbial stimuli were the same irrespective of whether the nodes were in the field of drainage of inflamed or noninflamed colonic segments.

Striking plasticity of DC responses to different microbial stimuli has previously been reported (4a, 9). Cytokine responses by DCs may also vary for different species of bacteria within the same genus (4). Discriminatory cytokine responses to different microbes enables the host to interpret the local environment and sense danger. This signaling is mediated by a series of pattern recognition receptors including Toll-like receptors and C-type lectins on the surface of DCs (1, 6, 19). The expression of these receptors is probably variant in different tissues. Another factor that may influence cytokine production in the different lymphoid compartments is the dose of bacteria exposed to the system. Variability of cytokine responses may also reflect heterogeneity within DC populations. Thus murine DCs from the intestinal Peyer’s patch promote IL-10 rather than IL-12 p40 responses, whereas the latter are more characteristic of splenic DCs (10). The results of the present study with human MLN support the murine evidence for regional specialization of DCs. Notwithstanding, the degree to which one may extrapolate across species is limited because normal murine responses to intestinal antigens are biased toward a Th2 profile, whereas human mucosal immune responses appear to have a Th1 bias (22).

Translocation of bacteria is an important issue in clinical medicine, and translocation was traditionally measured by culturing bacteria from the MLN. More recently, MLNs have been demonstrated to be important gatekeepers limiting bacterial access to the systemic circulation (17). The results of the present study have clinical implications because commensal bacteria, including those studied here, have been used as probiotics in animal models of IBD (18, 23) and are in human clinical trials (www.proeuropehealth.vtt.fi). Whether the numbers of bacteria used in our studies are clinically relevant is unknown but are likely to be relevant in the context of clinical conditions with increased gut permeability and a high rate of sepsis (e.g., IBD). Moreover, numbers of bacteria recovered from the periphery in experimentally infected animals are in the range of bacteria tested in this study (30). Finally, we (29) have previously demonstrated that probiotics administered parenterally have beneficial effects; therefore, it is important to
understand how the immune system perceives them in different locations. In this respect, it is noteworthy that although Lactobacilli are known to stimulate IL-12 responses from human peripheral blood (21), the more relevant responses are probably those from gut-associated lymphoid tissue. In contrast to peripheral blood, regulatory cytokines such as IL-10 and TGF-β were produced in preference to TNF-α and IL-12 by both PBMC- and MLNC-derived DCs. IL-10 was secreted not by MLNC-derived DCs. In contrast, L. salivarius was exposed in vitro to L. salivarius and B. infantis induced TNF-α production by peripheral blood-derived DCs (n = 3), which was not induced in MLNC-derived DCs (n = 5). In addition, L. salivarius induced IL-12 production by PBMC-derived DCs but not by MLNC-derived DCs. In contrast, S. typhimurium induced TNF-α and IL-12 production by both PBMC- and MLNC-derived DCs. IL-10 was secreted by PBMC- and MLNC-derived DCs upon coinoculation with L. salivarius and B. infantis, whereas PBMC-derived DCs alone secreted IL-10 in response to S. typhimurium. Top: IL-12, middle: TNF-α; bottom: IL-10. Results are expressed as mean cytokine levels ± SE after stimulation with 0 (nonstimulated) or 1 × 10⁷ bacterial cells. * Significant difference between nonstimulated cells compared with cells stimulated with bacteria (P < 0.05).

**DISCLOSURES**

L. O’Mahony, J. K. Collins, and F. Shanahan have been affiliated with a multidepartmental university campus-based research company (Alimentary Health Limited), which investigates host-flora interactions and the therapeutic manipulation of these interactions in various human and animal disorders. The content of this article was neither influenced nor constrained by this fact.

**REFERENCES**


