



## Review Article

### Review Article: Human Gut Flora

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#### ABSTRACT

#### Keywords

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The intestinal microflora is a complex ecosystem. An improved understanding of this hidden organ will reveal secrets that are relevant to human health and to several infectious, inflammatory and neoplastic disease processes. Given the ability of the immune response to rapidly counter infectious agents, it is striking that such a large density of microbes can exist in a state of synergy within the human host. The relevance and effect of resident bacteria on a host's physiology and pathology are extremely diverse. An ever-increasing body of evidence implicates the GI microbiota in defining states of health & disease. We review the literature in adult and pediatric GI microbiome studies, the emerging links between microbial community structure, function, infection and disease, and the approaches to manipulate this crucial ecosystem to improve host health. Manipulation of the flora is becoming a realistic therapeutic and prophylactic strategy for many infectious, inflammatory and even neoplastic diseases within the gut. Based on the influence of prenatal and early postnatal microbial exposures on the developing immune response to gut microbiome, aberrations in adulthood associated with chronic inflammatory diseases, have revealed the complexity of our dynamic relationship with microbes.

#### Introduction

The human gut is the natural habitat for a large and dynamic bacterial community. However, the relevance and effect of resident bacteria on a host's physiology and pathology has been well documented. Most bacterial species cannot be cultured, but modern molecular methods, such as broad-range sequencing of 16S ribosomal RNA from amplified bacterial nucleic acid extracted from faeces or biopsies, indicate evolutionary divergence that can be used to

identify and classify bacteria. The availability of bacterial sequence data has facilitated the development of molecular probes for fluorescence *in situ* hybridization, DNA microarrays and gene chips that can identify and enumerate specific species. These molecular approaches have been used to examine the individuality and stability of the flora over time and to detect shifts in its composition after weaning, exposure to antibiotics or dietary changes. Acid, bile and

pancreatic secretions hinder the colonization of the stomach and proximal small intestine by most bacteria. However, bacterial density increases in the distal small intestine, and in the large intestine rises to an estimated  $10^{11}$ – $10^{12}$  bacteria per gram of colonic content, which contributes to 60% of faecal mass. The fetal gut is sterile but colonization begins immediately after birth and is influenced by the mode of delivery, the infant diet, hygiene levels and medication (Gronlund *et al.*, 1999).

Probiotics and prebiotics are known to have a role in prevention or treatment of some diseases (www.webmd).

### **Patho-physiology**

Host–flora communication at the mucosal surface:

Host defence requires an accurate interpretation of the microenvironment to distinguish commensal organisms from episodic pathogens and a precise regulation of subsequent responses. The epithelium provides the first sensory line of defence and active sampling of resident bacteria, pathogens and other antigens is mediated by three main types of immunosensory cell.

First, surface *enterocytes* serve as afferent sensors of danger within the luminal microenvironment by secreting chemokines and cytokines those alert and direct innate and adaptive immune responses to the infected site (Shanahan, 2005).

Second, *M cells* that overlie lymphoid follicles sample the environment and transport luminal antigens to subadjacent dendritic cells and other antigen-presenting cells.

Third, intestinal *dendritic cells* themselves have a pivotal immunosensory role and can

directly sample gut contents by either entering or extending dendrites between surface enterocytes without disrupting tight junctions (Rescigno *et al.*, 2001). Dendritic cells can ingest and retain live commensal bacteria and travel to the mesenteric lymph node where immune responses to commensal bacteria are induced locally (Macpherson and Uhr, 2004). Thus, acting as a gatekeeper, the mesenteric lymph node prevents access of commensal bacteria to the internal milieu.

The ability of immunosensory cells to discriminate pathogenic from commensal bacteria is mediated, in part, by two major host pattern recognition receptor (*PRR*) systems—the family of Toll-like receptors (*TLRs*) and the Nucleotide-binding Oligomerization Domain/caspase recruitment domain isoforms (*NOD/CARD*; Cario, 2005). These PRRs have a fundamental role in immune-cell activation in response to specific microbial-associated molecular patterns.

Effector mechanisms of the commensal flora:

Host inflammatory responses to pathogenic bacteria and other stress signals are pivotally controlled by the transcription factor nuclear factor (*NF*)-*κB*. Several distinct mechanisms by which commensal bacteria limit *NF-κB* signaling have been elucidated.

These include inhibition of epithelial proteasome function. Degradation of the *NF-κB* counter-regulatory factor or nuclear export of the *NF-κB* subunit, p65, through a peroxisome proliferator-activated receptor (*PPAR*) dependent pathway (Kelly *et al.*, 2004; Neish *et al.*, 2000; Petrof *et al.*, 2004).

Some commensal bacteria might inhibit specific signalling via *TLR4* by elevating

PPAR expression and uncoupling NF- $\kappa$ B-dependent target genes in a negative-feedback loop (Dubuquoy *et al.*, 2003).

Induction of transforming growth factor- $\beta$  and nerve growth factor, and mitogen activated protein kinase and protein kinase B pathways have also been implicated in the anti-inflammatory effects mediated by various commensal bacteria (Ma *et al.*, 2004; Yan and Polk, 2002)

Molecular mimicry of host molecules: Commensal bacteria display surface molecules resembling those of the surface of the host, could contribute to immune hyporesponsiveness.

### **Factors affecting gut flora development**

**Obesity:** Compared with lean individuals, obese subjects exhibit a dramatic tenfold shift in the ratio of Firmicutes to Bacteroidetes (from 3:1 to 35:1), two of the major phyla present in the human GI tract (Ley *et al.*, 2006). This altered community structure is associated with a shift in function, resulting in increased energy harvest from ingested food; unexpended excess energy is deposited as adipose tissue (Turnbaugh *et al.*, 2006).

**Diet:** Diet can dramatically impact the composition of the gut microbial community (Turnbaugh *et al.*, 2006). A high-fat diet has been associated with an increase in Firmicutes and Proteobacteria and a concomitant decrease in Bacteroidetes in both wild-type mice (Hildebrandt *et al.*, 2009). In humans, a high-fat diet resulted in a similar phylogenetic shift in the GI microbiome associated with obesity; this restructuring is largely due to dietary selective pressure, which promotes

organisms optimally poised to metabolize and import readily available carbon sources, particularly simpler sugars, such as glucose, fructose and sucrose (Turnbaugh *et al.*, 2008).

**Administration of antibiotics:** Antibiotic administration dramatically impacts the native microbial community, leading to an unintentional state of dysbiosis (Collins *et al.*, 2009). Despite the dramatic impact antibiotic administration has on the gut microbiota, the community in healthy adults appears to be relatively resilient; once administration of antibiotics has ceased, the gut microbiome largely returns to a pretherapy consortium after 4 weeks (Dethlefsen *et al.*, 2008). However, this dramatically alters the composition of the gut microbiome.

**Environmental exposure:** Maternal exposure to environmental stimuli, particularly microbes during pregnancy, plays an important role in postnatal immune functioning and, in particular, the subsequent development of allergic disease (Ege *et al.*, 2006; Wegienka *et al.*, 2009). Schaub *et al.* (2009) demonstrated that mothers exposed to farms and farm animals during pregnancy were less likely to have children who developed allergies and asthma. These prenatal exposures were associated with increased number and function of cord blood T regulatory (Treg) cells, which are linked to lower Th2 cytokine secretion (increased Th2 cytokine secretion is a characteristic of an allergic response). The exposure to household pets (cats and dogs) has also been shown to protect against allergic disease development (Wegienka *et al.*, 2009) and it is hypothesized that this protection is, as with farm animal exposures, mediated via microbes. Pet exposure is associated with lower cord blood IgE levels (Aichbhaumik

*et al.*, 2008), which is particularly pertinent given the crucial role that IgE plays in fetal immune system functioning and that elevated cord blood IgE levels associated with subsequent development of allergic disorders.

**Serious illness and Long-term intravenous feeding:** Although a well-functioning human intestine teems with a variety of microbial life, serious illness, long-term intravenous feeding, and wipe out much of this diversity. When a patient spends a long time in ICU, “the gut undergoes near-complete ecologic collapse (www.webmd).

**Vaginal delivery:** Leads to exposure to maternal vaginal microbiome, typically composed of commensal organisms commonly found in the lower GI tract (Tannock *et al.*, 1990). These infants typically possess higher abundances of certain *Bifidobacterium* and *Bacteroides* species, which have been associated with health-promoting effects.

**Breast feed Vs formula – based diet:** Breast milk provides nutritional support, it facilitates transfer of bioactive agents, for example, maternal secretory IgA, which provides passive immunoprotection and sequester commensal species in the neonatal intestine and promote biofilm formation an aspect that has been argued to facilitate colonization by protective native gut bacteria (immune inclusion) and prevent colonization by pathogenic species (immune exclusion) (Bollinger *et al.*, 2003; Bollinger *et al.*, 2006). Other components of breast milk modulate the developing mucosal immune response, while the presence of indigestible oligosaccharides promotes the growth of specific bacterial families such as the Bifidobacteriaceae and may act as decoy ligands for pathogens, preventing their mucosal attachment. Thus the components

of breast milk serve to both directly and indirectly enhance mucosal barrier function and shape immune development. In addition to protection against allergic disease development, breastfeeding has also been associated with defense against neonatal diarrhea, necrotizing colitis, obesity (meta analysis is provided in (Owen *et al.*, 2005) and Type II diabetes.

### **Disease and disorders due to alteration of gut flora**

Aberrations in gut microbiota associated with a number of diseases and disorders including allergic disease development (Penders *et al.*, 2007; Penders *et al.*, 2007), colon cancer (Scanlan *et al.*, 2008), and even progression and severity of HIV (Gori *et al.*, 2008). Disruption of the gut microbiome, termed dysbiosis, is frequently accompanied by overgrowth of pathogenic bacteria or fungi, in conjunction with significant loss of microbial diversity or key functional groups and an inflammatory response by the host (Manichanh *et al.*, 2006; Willing *et al.*, 2009), which contributes to disease development (Gori *et al.*, 2008). Dysbiosis has been associated with an imbalance between populations of inflammation-mediating T-helper cells (Th1, Th2 and Th17) and anti-inflammatory Treg cells. Prolonged overproduction of Th1- and Th17-associated cytokines has been linked with Inflammatory Bowel Disease (IBD) (overproduction of Th1 for Crohn's disease (Fuss IJ *et al.* 1996) and Th17 for both CD and ulcerative colitis (Fujino *et al.*, 2003). IBD patient appears unable to reprogram towards a noninflammatory state suggesting that low levels of certain microbial species maintain a proinflammatory state (Hanauer *et al.*, 2006). At a functional level, the butyrate-producers, which belong to the *Clostridium leptum* group of the Firmicutes, are less abundant in the GI microbiome of

IBD patients. Butyrate is an essential regulator of gene expression, inflammation, differentiation and apoptosis, and is a major energy source for the mucosa-associated microbial community.

*Faecalibacterium prausnitzii*, a butyrate-producing bacterium with anti-inflammatory properties (Willing *et al.*, 2009), is significantly reduced in abundance in the

ileum of CD patients (Willing *et al.*, 2009; Frank *et al.*, 2007) in parallel with increased numbers of *E. coli* (Willing *et al.*, 2009). This emphasizes the key role a number of distinct bacterial species play in maintaining inflammatory homeostasis and that loss of key functional organisms leads to pathogen overgrowth associated with chronic inflammatory illness.

**Table.1** Most common anaerobic and aerobic genera (Ann M.O’Hara and Fergus Shanahan, 2006)

Anaerobic genera	Aerobic genera
Bifidobacterium	<i>Escherichia</i>
Clostridium	<i>Enterococcus</i>
Bacteroides	<i>Streptococcus</i>
Eubacterium	<i>Klebsiella</i>

**Table.2** Functions of intestinal flora (Ann M.O’Hara and Fergus Shanahan, 2006)

Protective function	Structural function	Metabolic function
<ol style="list-style-type: none"> <li>1. Pathogen displacement.</li> <li>2. Nutrient and receptor competition with pathogen</li> <li>3. Production of antimicrobial factors e.g. bacteriocins, lactic acids.</li> </ol>	<ol style="list-style-type: none"> <li>1. Barrier fortification.</li> <li>2. Induction of IgA Antibody</li> <li>3. Immune system development</li> </ol>	<ol style="list-style-type: none"> <li>1. Control intestinal epithelial cell differentiation and proliferation.</li> <li>2. Metabolize dietary carcinogens.</li> <li>3. Synthesize vitamins e.g. vit-K, biotin, folate.</li> <li>4. Ferments non-digestible dietary residue</li> <li>5. Iron absorption</li> <li>6. Salvage of energy.</li> </ol>

**Table.3** Diseases and disorders due to aberrations in the human gut microbiome

Disease /disorder	Role of microbiome	Recent finding
Atopy and asthma (Penders <i>et al.</i> , 2007)	<p>Pre- and postnatal microbial exposures appear key to appropriate immune development.</p> <p>Mode of delivery and nutrient uptake are important factors for GI community development and protection against subsequent atopic disease development.</p>	<ul style="list-style-type: none"> <li>• Mothers exposed to farm animals during pregnancy are less likely to have children who develop asthma and allergies</li> <li>• Early exposure to cat(s) and/or dog(s) is protective against atopic diseases, presumed to be microbially mediated.</li> <li>• Infants born through the birth canal are exposed to and colonized by specific <i>Bifidobacteria</i> and <i>Bacteroides</i> species</li> <li>• Breast-fed infants possess functionally distinct GI microbiomes compared with formula-fed children.</li> </ul>
Colon cancer (CC) (Scanlan <i>et al.</i> , 2008)	<p>High abundance of <i>Clostridium leptum</i> and <i>Clostridium coccoides</i> subgroups in CC patient GI bacterial communities.</p>	<ul style="list-style-type: none"> <li>• Overall bacterial diversity increased for CC patients compared with healthy controls</li> <li>• CC patients exhibited GI bacterial community instability compared with healthy controls</li> <li>• Microbial butyrate production is thought to reduce the chances of CC development (Willing <i>et al.</i>, 2009)</li> </ul>

<p>HIV (Gori <i>et al.</i>, 2008)</p>	<p>Gut microbiome dysbiosis may be critical for pathogenesis</p>	<ul style="list-style-type: none"> <li>• Dysbiosis and intestinal inflammation may be critical to impairment of the GI microbial structure and function in early stages of HIV infection.</li> <li>• Low abundance of Bifidobacteria and lactobacilli detected in gut microbiomes of early-stage HIV infection (Willing <i>et al.</i>, 2009)</li> </ul>
<p>IBD (Fuss <i>et al.</i>, 1996; Zhang <i>et al.</i>, 2007)</p>	<ul style="list-style-type: none"> <li>• Immune response to gut microbial Community.</li> <li>• Composition of GI microbiota contributes to inflammation.</li> <li>• Treg-promoting organisms depleted; overgrowth of bacteria that induce proinflammatory Th17 cell populations.</li> </ul>	<p><b>Crohn's disease (IBDC)</b></p> <ul style="list-style-type: none"> <li>• Characteristics of GI dysbiosis include lower counts of <i>Clostridium leptum</i>, <i>Bacteroides uniformis</i>, Firmicutes, <i>Bacteroides</i> and higher abundances of <i>E. coli</i>, Proteobacteria and <i>Bacteroides ovatus</i></li> <li>• Lower number of <i>Faecalibacterium prausnitzii</i>, butyrate producing bacterium, found in parallel with increased <i>E. coli</i>.</li> </ul> <p><b>Ulcerative colitis (IBDU)</b></p> <ul style="list-style-type: none"> <li>• Lower levels of Bifidobacteria and <i>Clostridium coccoides</i> reported in comparison to healthy individuals</li> <li>• Differential <i>Clostridium leptum</i> and lactobacilli profiles identified by DGGE analysis of IBDU and healthy subjects (Zhang <i>et al.</i>, 2007)</li> </ul>

CC: Colon cancer; DGGE: Density gradient gel electrophoresis; GI: Gastrointestinal; IBD: Inflammatory bowel disease; IBDC: Irritable bowel disease–Crohn's disease; IBDU: Irritable bowel disease–ulcerative colitis; IBS: Irritable bowel syndrome; NEC: Necrotizing enterocolitis.

## **Role of probiotics**

Owing to the increased prevalence of diseases and disorders associated with gut microbiota imbalances (Table 3) and the fact that traditional treatments such as antibiotic administration appear to have the potential for long-term disruption, microbial manipulation of the host microbiome to treat chronic diseases has become the focus of recent renewed interest. Manipulation may be elicited through pro-, pre- or symbiotic.

**Probiotics:** First suggested by Metchnikoff in 1907, probiotic therapy represents alteration of the gut microbiota by supplementation with live microorganisms that function to inhibit pathogen adherence to the mucosa

1. improve the intestinal epithelial and mucosal barrier function
2. produce bacteriocins
3. increase IgA production
4. downregulate proinflammatory cytokine secretion.

Prebiotics, originally defined as nondigestible food ingredients that improve host health by stimulating the growth or activity of colonic bacteria, have now been reclassified to include components that are resistant to gastric acidity, hydrolysis by host enzymes and absorption by the upper gastrointestinal, are fermented by the gut microbiota, and stimulate growth of microbial species beneficial to the host's health.

Synbiotics are supplements composed of a combination of both probiotics and prebiotics.

Prebiotics also represent a promising approach for the management of inflammatory diseases. They have the advantage of promoting subsets of existing

native GI bacterial community members (e.g., Bifidobacteria) capable of degrading them and can increase production of important anti-inflammatory compounds, such as butyrate, without the conventional caveats of probiotic competitiveness or colonization efficiency.

Host-microbe interactions occur primarily along mucosal surfaces, and one of the largest interfaces is the human intestinal mucosa. The intestine is adapted to bidirectional host flora exchange and harbours a diverse bacterial community that is separated from the internal milieu by only a single layer of epithelial cells. Enteric bacteria form a natural defence barrier and exert numerous protective, structural and metabolic effects on the epithelium collectively, the flora has a metabolic activity equal to a virtual organ within an organ (Ann M.O'Hara and Fergus Shanahan, 2006).

Manipulation of the flora is becoming a realistic therapeutic and prophylactic strategy for many infectious, inflammatory and even neoplastic diseases within the gut. However, the promise of pharmabiotics is unlikely to be completely fulfilled without greater attention to the secrets held within the forgotten inner organ represented by the enteric microflora. Based on the influence of prenatal and early postnatal microbial exposures on the developing immune response to gut microbiome, aberrations in adulthood associated with chronic inflammatory diseases, have revealed the complexity of our dynamic relationship with microbes. Relatively recent changes in lifestyle, diet and the use of antimicrobials are just some of the factors implicated in increased prevalence of a range of inflammatory disorders that have a demonstrated basis in altered GI microbial community structure and function.

With respect to pre-, pro-, symbiotics initial results are promising, even though randomized, large-scale studies with well-characterized patient populations who are supplemented with controlled dosages of specific well-characterized supplements, and whose samples are examined using high-resolution microbiome composition and functional analyses, are necessary to fully appreciate the therapeutic effects.

## References

- Aichbhaumik N, Zoratti EM, Strickler R, *et al.* Prenatal exposure to household pets influences fetal immunoglobulin E production. *Clin Exp Allergy* 2008;38(11):1787–1794.
- Ann M.O'Hara and Fergus Shanahan, 2006. The gut flora as a forgotten organ. Alimentary Pharmabiotic Centre, University College Cork, National University of Ireland, Cork, Ireland.
- Bollinger RR, Everett ML, Palestrant D, Love SD, Lin SS, Parker W. Human secretory immunoglobulin A may contribute to biofilm formation in the gut. *Immunology* 2003;109(4):580–587.
- Bollinger RR, Everett ML, Wahl SD, Lee YH, Orndorff PE, Parker W. Secretory IgA and mucin-mediated biofilm formation by environmental strains of *Escherichia coli*: role of type 1 pili. *Mol Immunol* 2006;43(4):378–387.
- Collins S, Denou E, Verdu E, Bercik P. The putative role of the intestinal microbiota in the irritable bowel syndrome. *Dig Liver Dis* 2009;41(12):850–853.
- Dethlefsen L, Huse S, Sogin ML, Relman DA. The pervasive effects of an antibiotic on the human gut microbiota, as revealed by deep 16S rRNA sequencing. *PLoS Biol* 2008;6 (11):e280. Culture-independent analysis of how antibiotic administration reduced intestinal microbial diversity, which also demonstrated a rapid return to the pretreatment microbiota following cessation of treatment, underscoring the resiliency of the adult gut microbiota to perturbations.
- Ege MJ, Bieli C, Frei R, *et al.* Prenatal farm exposure is related to the expression of receptors of the innate immunity and to atopic sensitization in school-age children. *J Allergy Clin Immunol* 2006;117(4):817–823.
- Frank DN, St Amand AL, Feldman RA, Boedeker EC, Harpaz N, Pace NR. Molecular-phylogenetic characterization of microbial community imbalances in human inflammatory bowel diseases. *Proc Natl Acad Sci USA* 2007;104(34):13780–13785.
- Fujino S, Andoh A, Bamba S, *et al.* Increased expression of interleukin 17 in inflammatory bowel disease. *Gut* 2003;52(1):65–70.
- Fuss IJ, Neurath M, Boirivant M, *et al.* Disparate CD4+ lamina propria (LP) lymphokine secretion profiles in inflammatory bowel disease: Crohn's disease LP cells manifest increased secretion of IFN- $\gamma$ , whereas ulcerative colitis LP cells manifest increased secretion of IL-5. *J Immunol* 1996;157 (3):1261–1270.
- Gori A, Tincati C, Rizzardini G, *et al.* Early impairment of gut function and gut flora supporting a role for alteration of gastrointestinal mucosa in human immunodeficiency virus pathogenesis. *J Clin Microbiol* 2008;46(2):757–758.
- Hanauer SB. Inflammatory bowel disease: epidemiology, pathogenesis, and therapeutic opportunities. *Inflamm Bowel Dis* 2006;12(5):S3–S9.
- Hildebrandt MA, Hoffmann C, Sherrill-Mix SA, *et al.* High-fat diet determines the composition of the murine gut microbiome independently of obesity. *Gastroenterology* 2009;137(5):1716–1724. e1–2.
- Ley RE, Turnbaugh PJ, Klein S, Gordon JI. Microbial ecology: human gut microbes associated with obesity. *Nature* 2006; 444 (7122):1022–1023.

- Manichanh C, Rigottier-Gois L, Bonnaud E, *et al.* Reduced diversity of faecal microbiota in Crohn's disease revealed by a metagenomic approach. *Gut* 2006;55(2):205–211.
- Owen CG, Martin RM, Whincup PH, Smith GD, Cook DG. Effect of infant feeding on the risk of obesity across the life course: a quantitative review of published evidence. *Pediatrics* 2005;115(5):1367–1377.
- Penders J, Stobberingh EE, van den Brandt PA, Thijs C. The role of the intestinal microbiota in the development of atopic disorders. *Allergy* 2007;62(11):1223–1236.
- Penders J, Thijs C, van den Brandt PA, *et al.* Gut microbiota composition and development of atopic manifestations in infancy: the KOALA Birth Cohort Study. *Gut* 2007;56(5):661–667. [PubMed: 17047098] Infant gut microbial colonization events at 1 month are associated with the subsequent development of atopic diseases in childhood.
- Scanlan PD, Shanahan F, Clune Y, *et al.* Culture-independent analysis of the gut microbiota in colorectal cancer and polyposis. *Environ Microbiol* 2008;10(3):789–798.
- Schaub B, Liu J, Höppler S, *et al.* Maternal farm exposure modulates neonatal immune mechanisms through regulatory T cells. *J Allergy Clin Immunol* 2009;123(4):774–782.
- Tannock GW, Fuller R, Smith SL, Hall MA. Plasmid profiling of members of the family Enterobacteriaceae, Lactobacilli, and Bifidobacteria to study the transmission of bacteria from mother to infant. *J Clin Microbiol* 1990; 28(6):1225–1228.
- Turnbaugh PJ, Bäckhed F, Fulton L, Gordon JI. Diet-induced obesity is linked to marked but reversible alterations in the mouse distal gut microbiome. *Cell Host Microbe* 2008;3(4):213–223.
- Turnbaugh PJ, Ley RE, Mahowald MA, Magrini V, Mardis ER, Gordon JI. An obesity-associated gut microbiome with increased capacity for energy harvest. *Nature* 2006;444(7122):1027–1031.
- Wegienka G, Havstad S, Zoratti EM, *et al.* Regulatory T cells in prenatal blood samples: variability with pet exposure and sensitization. *J Reprod Immunol* 2009;81(1):74–81. [PubMed: 19545906]
- Willing B, Halfvarson J, Dicksved J, *et al.* Twin studies reveal specific imbalances in the mucosa-associated microbiota of patients with ileal Crohn's disease. *Inflamm Bowel Dis* 2009;15(5):653–660.
- Zhang M, Liu B, Zhang Y, Wei H, Lei Y, Zhao L. Structural shifts of mucosa-associated lactobacilli and *Clostridium leptum* subgroup in patients with ulcerative colitis. *J Clin Microbiol* 2007;45(2): 496–500.