The following full text is a publisher's version.

For additional information about this publication click this link.
http://hdl.handle.net/2066/97823

Please be advised that this information was generated on 2020-02-15 and may be subject to change.
Differential Toll-Like Receptor Recognition and Induction of Cytokine Profile by Bifidobacterium breve and Lactobacillus Strains of Probiotics

Theo S. Plantinga, Wendy W. C. van Maren, Jeroen van Bergenhenegouwen, Marjolijn Hameetman, Stefan Nierkens, Cor Jacobs, Dirk J. de Jong, Leo A. B. Joosten, Belinda van’t Land, Johan Garssen, Gosse J. Adema and Mihai G. Netea

Published Ahead of Print 2 February 2011.

Updated information and services can be found at:
http://cvi.asm.org/content/18/4/621

These include:

REFERENCES
This article cites 48 articles, 22 of which can be accessed free at:
http://cvi.asm.org/content/18/4/621#ref-list-1

CONTENT ALERTS
Receive: RSS Feeds, eTOCs, free email alerts (when new articles cite this article), more»

Information about commercial reprint orders: http://journals.asm.org/site/misc/reprints.xhtml
To subscribe to another ASM Journal go to: http://journals.asm.org/site/subscriptions/
Differential Toll-Like Receptor Recognition and Induction of Cytokine Profile by *Bifidobacterium breve* and *Lactobacillus* Strains of Probiotics\(^7\)

Theo S. Plantinga, 1,2† Wendy W. C. van Maren, 3† Jeroen van Bergenhenegouwen, 4 Marjolijn Hameetman, 3 Stefan Nierkens, 3 Cor Jacobs, 1,2 Dirk J. de Jong, 5 Leo A. B. Joosten, 1,2 Belinda van’t Land, 4,6 Johan Garssen, 4,6 Gosse J. Adema, 3 and Mihai G. Netea 1,2,*

Department of Medicine, 1 Nijmegen Institute for Infection, Inflammation and Immunity (N4i), 2 Department of Tumor Immunology, 3 and Department of Gastroenterology and Hepatology, 5 Radboud University Nijmegen Medical Centre, Nijmegen, Netherlands; Danone Research, Center for Specialised Nutrition, Wageningen, Bosrandweg 20, 6704 PH Wageningen, Netherlands; and Utrecht Institute for Pharmaceutical Sciences (UIPS), Utrecht University, Sorbonnelaan 16, 3584 CA Utrecht, Netherlands

Received 18 November 2010/Returned for modification 8 December 2010/Accepted 25 January 2011

The use of probiotics as a food supplement has gained tremendous interest in the last few years as beneficial effects were reported in gut homeostasis and nutrient absorption but also in immunocompromised patients, supporting protection from colonization or infection with pathogenic bacteria or fungi. As a treatment approach for inflammatory bowel diseases, a suitable probiotic strain would ideally be one with a low immunogenic potential. Insight into the immunogenicities and types of T-cell responses induced by potentially probiotic strains allows a more rational selection of a particular strain. In the present study, the bacterial strains *Bifidobacterium breve* (NumRes 204), *Lactobacillus rhamnosus* (NumRes1), and *Lactobacillus casei* (DN-114 001) were compared concerning their capacity to induce inflammatory responses in terms of cytokine production by human and mouse primary immune cells. It was demonstrated that the *B. breve* strain induced lower levels of the proinflammatory cytokine gamma interferon (IFN-γ) than the tested *L. rhamnosus* and *L. casei* strains. Both *B. breve* and lactobacilli induced cytokines in a Toll-like receptor 9 (TLR9)-dependent manner, while the lower inflammatory profile of *B. breve* was due to inhibitory effects of TLR2. No role for TLR4, NOD2, and C-type lectin receptors was apparent. In conclusion, TLR signaling is involved in the differentiation of inflammatory responses between probiotic strains used as food supplements.

In recent years, probiotic supplements have been suggested to provide health benefits. Subsequently, the use of specific probiotic strains as safe supplements for human consumption has been approved. Probiotic strains are classified as being live microorganisms which, when administered in sufficient amounts, confer a health benefit to the host (11). This health benefit could comprise more efficient digestion, nutrient absorption, or higher resistance to pathogenic bacteria in the gut.

Microorganisms from the genera *Lactobacillus* and *Bifidobacterium* are often considered as probiotic candidates. All these bacteria are Gram positive, (facultative) anaerobe microorganisms that are common commensals in the human gastrointestinal tract. These bacteria are currently used in probiotic dietary products, and several lines of evidence have demonstrated their beneficial effects on gut homeostasis (6, 16, 20, 38, 44). In addition, mouse studies have been conducted to investigate the immunomodulatory capacity of these potential probiotics, with similar findings (18, 23, 43, 46). These effects range from downregulation of cytokine responses in immune cells to induction of apoptosis in T cells and vaccine-improving properties (4, 7, 8, 10, 13).

Previous studies indicate that the ability of probiotics to induce the secretion of various cytokines is mediated to a large extent by cell wall components (13, 25, 40). Cell wall components elicit these responses through recognition by pattern recognition receptors (PRRs), germ line-encoded receptors expressed on innate immune cells that are specialized to bind these bacterial substances. Examples of these receptors, either membrane bound or localized intracellularly, are the Toll-like receptors (TLRs), C-type lectin receptors (CLRs) (such as dectin 1, mannose receptor, or DC-SIGN), and nucleotide-binding oligomerization domain (NOD)-like receptors (NLRs) (such as the peptidoglycan receptor NOD2). For the triggering of intracellular receptors, the process of phagocytosis is required, whereas membrane-bound receptors detect their ligand on the cell surface and in some cases facilitate phagocytosis (2). Subsequently, downstream intracellular signaling from these receptors results in the modulation of cytokine responses (30).

The PRRs that are responsible for the recognition of these strains, resulting in induction of cytokine responses and activation of the immune system, remain elusive. Therefore, in the present study the capacity of the bacterial strains *Bifidobacterium breve* (NumRes204), *Lactobacillus rhamnosus* (NumRes1), *Lactobacillus casei* (DN-114 001) to induce immune responses in

---

\(^*\) Corresponding author. Mailing address: Department of Medicine, Radboud University Nijmegen Medical Centre, internal postal code 463, P.O. Box 9101, 6500 HB Nijmegen, Netherlands. Phone: 31-24-3618819. Fax: 31-24-3541734. E-mail: m.netea@aiG.umcn.nl.

\(^†\) These authors contributed equally to the study.

\(^\ddagger\) Published ahead of print on 2 February 2011.
peripheral blood mononuclear cells (PBMCs) has been examined for both healthy volunteers and NOD2-deficient Crohn’s disease (CD) patients. Furthermore, the role of several PRRs of the innate immune system that could mediate these immune responses, including TLRs, CLRs, and NLRs, has been investigated in both human and mouse cells.

MATERIALS AND METHODS

Subjects. Healthy volunteers and Crohn’s disease patients were recruited at the Radboud University Nijmegen Medical Centre, Nijmegen, Netherlands. The study was approved by the Ethical Committee of the Radboud University, and the volunteers gave informed consent. At the time of donation, Crohn’s disease patients homozygous for the NOD2 frameshift mutation were in a quiescent phase, i.e., a prolonged period of at least 3 months of mild disease without relapses or exacerbations in the absence of immunomodulatory therapy. Also, they had received no immunomodulatory or anti-inflammatory medications for the last 3 months.

Mice. Wild-type C57BL/6 mice were obtained from Charles River. WIGA (Sulzfeld, Germany) GmbH. TLR2 knockout mice and TLR4 knockout mice, with a C57BL/6 background, were kindly provided by S. Akira (Osaka University, Osaka, Japan) (42). All animal experiments were approved by the Animal Experiment Committee of Radboud University Nijmegen Medical Centre, Nijmegen, Netherlands, and were performed in accordance with institutional and national guidelines.

Reagents. Blocking monoclonal antibodies (Abs) of the innate immune receptors TLR2 (clone 2 T2.5) and DC-SIGN (clone A2ZD1), including the IgG1 isotype control, were purchased from eBioscience, Coulter Beckman, and R&D Systems, respectively, and were all used in a concentration of 10 μg/ml. Blocking reagents of the receptors TLR4 (Bartonella quintana lipopolysaccharide, [31], [1 μg/ml), TLR9 (Cpg ODN TTAGGG, 25 μg/ml; Invivogen), mannose receptor (mannan, 100 μg/ml; Sigma), and dectin 1 (laminarin, 100 μg/ml; Sigma), and of phagocytosis (cytochalasin B, 1 μg/ml; Biomed International) were used.

Bacterial fermentation and enumeration. Two Lactobacillus strains (Nannococcus and N-114 001) and a Bifidobacteria breve strain (NumRes240) were grown at 37°C in a 400-ml reactor containing MRS supplemented with 0.5% H2, 5% CO2, and 90% N2 for 20:1, and cytokines were measured at different time points.

RESULTS

Cytokine production capacity of PBMCs induced by potentially probiotic strains. To study the immunostimulatory capacities of the bacterial strains B. breve, L. rhamnosus, and L. casei, PBMCs were stimulated with bacterial cells at a ratio of 20:1, and cytokines were measured at different time points. Important differences were observed between induction of cytokine production by the bacterial strains. Most importantly, while all monocye-derived cytokines can be induced by all probiotic strains studied, only lactobacilli, but not B. breve, stimulated production of IFN-γ (Fig. 1).
Accordingly, additional experiments with TLR2-transfected HEK293 cells revealed that *B. breve* but not *L. rhamnosus* or *L. casei* induces TLR2 signaling (Fig. 3B). Blocking of TLR4 had no effect on cytokine production. These experiments were also performed with mouse splenocytes, either wild type, TLR2 knockout (KO), or TLR4 KO. Consistent with the human data, IFN-γ responses in TLR2 KO cells but not in TLR4 KO cells were different from those in wild-type cells after stimulation with *B. breve* (Fig. 3C). Compared to the human data, the TLR2 KO splenocytes also exhibited a further increase in the production of IFN-γ relative to results with wild-type splenocytes after stimulation with *L. rhamnosus* and *L. casei*, whereas the TLR4 KO cells did not. Blocking the C-type lectin receptors dectin 1, mannose receptor, and DC-SIGN did not significantly influence probiotic-induced cytokine production (data not shown).

**Role of intracellular receptors.** Microbial recognition at the level of the cell membrane is complemented by pattern recognition in the intracellular compartment by TLRs (e.g., TLR9) or NLRs (e.g., NOD2). Therefore, the role of phagocytosis was studied by using the phagocytosis inhibitor cytochalasin B. Cytochalasin B decreased cytokine responses for virtually all cytokines, suggesting an important role for intracellular recognition receptors (Fig. 4). Therefore, the role of intracellular PRRs, such as TLR9 and NOD2, in recognition of these bacterial strains was studied. Blocking of the TLR9 receptor resulted in a profound decrease in IL-10 and IFN-γ responses after stimulation of cells with either bacterial strain (Fig. 5).
For the other cytokines measured, TNF-α, IL-1β, and IL-6 concentrations revealed no differences between the conditions (data not shown). To assess the role of the intracellular PRR NOD2, cells from healthy subjects with functional NOD2 were compared with cells obtained from Crohn’s disease (CD) patients that are homozygous for the 1007fsinsC frameshift mutation in NOD2, leading to a loss of function of the protein. These analyses revealed no apparent differences between the two groups after stimulation of these cells with the bacterial strains (Fig. 6).

**DISCUSSION**

Nowadays, dietary products are widely supplemented with probiotics, i.e., live microorganisms that may have the ability to provide a health benefit to the host. Desirable features of a
probiotic strain are protective colonization of the intestinal tract and increasing efficiency of digestion and nutrient absorption but also a low capacity to cause immune responses to deviate toward Th1 and/or Th17 immune responses, which are associated with intestinal pathology (32, 37, 39). Hence, the potential of probiotics as a therapeutic moiety in diseases involving the gastrointestinal tract (e.g., infections, inflammatory bowel disease, and colon cancer) has been suggested (12, 33, 47). The rational use of probiotics in health and disease, however, needs a detailed understanding of the recognition pathways that can activate host defense by probiotics.

The potential of probiotics to modulate immune responses may represent an important factor for their therapeutic application. In fact, it is known that the release of TNF-α by inflamed Crohn’s disease mucosa can be significantly reduced by coculture with L. casei DN-114 001 (5). More specifically, L. casei can counteract the proinflammatory effects of Escherichia coli on Crohn’s disease-inflamed mucosa by specific downregulation of key proinflammatory mediators (19). In the present study, we compared the inflammatory properties of three different bacterial strains, B. breve, L. rhamnosus, or L. casei. Fold induction was calculated as the ratio of experimental activity to control activity. Values are means ± SD; n = 4. (C) Cytokine production capacity of IFN-γ by splenocytes obtained from wild-type (WT), TLR2KO, and TLR4 KO mice stimulated with the bacterial strains. Values are means ± SEM; n = 6; *, P < 0.05.

FIG. 3. (A) Production of IL-12, IL-10, and TNF-α after stimulation of mouse bone marrow-derived dendritic cells with Pam3Cys, L. rhamnosus, or L. casei for 24 or 48 h. Values are means ± SEM; n = 4. (B) NF-κB activity after overnight stimulation of TLR2-transfected HEK293 cells with different CFU/cell ratios of B. breve, L. rhamnosus, or L. casei. Fold induction was calculated as the ratio of experimental activity to control activity. Values are means ± SEM; n = 4. (C) Cytokine production capacity of IFN-γ by splenocytes obtained from wild-type (WT), TLR2KO, and TLR4 KO mice stimulated with the bacterial strains. Values are means ± SEM; n = 6; *, P < 0.05.

VOL. 18, 2011 PROBIOTICS AND IMMUNE REGULATION 625
severely decreased production of IL-10 and IFN-γ, indicating that these bacterial strains contain immune-stimulatory double-stranded DNA (dsDNA) containing unmethylated CpG sequences. In contrast, no differences were observed when the action of other PRRs, such as TLR4, dectin 1, mannose receptor, DC-SIGN, and NOD2, was inhibited, indicating that these receptors have a minor role in recognition of bacterial strains. The role of TLR9 in recognition of bacterial (3, 14) and fungal (26, 34) DNA is well known; however, its role in the induction of innate immune responses by probiotics in primary human cells had not been demonstrated until now.

Recognition of B. breve by TLR2 had an effect opposite to that with TLR9. Blocking of TLR2 with a specific antibody stimulated cytokine responses induced by B. breve, including TNF-α, IL-1β, and IFN-γ. Interestingly, no role for TLR2 could be demonstrated in L. rhamnosus- and L. casei-induced cytokine responses, indicating either that these bacteria lack TLR2 ligands in their cell wall or, perhaps more likely, that potential TLR2 ligands are masked. Of note, bone marrow-

FIG. 4. Cytokine production capacity for TNF-α, IL-1β, IL-6, IL-10, and IFN-γ by PBMCs obtained from healthy volunteers and stimulated with the bacterial strains in the absence or presence of cytochalasin B. Values are means ± SEM; n = 6; *, P < 0.05.
derived murine dendritic cells, which are highly susceptible to TLR2 agonists, also failed to elicit noteworthy cytokine responses after exposure to these bacterial strains. In addition, data from TLR2-overexpressing human embryonic kidney (HEK293) cells containing an NF-κB reporter construct showed NF-κB induction upon incubation with *B. breve* whereas *L. rhamnosus* and *L. casei* were unable to do so. To complement and support the human data, additional experiments were performed with mouse splenocytes that were either wild type or deficient in TLR2 or TLR4. In these experiments, IFN-γ production was increased in TLR2 KO cells but was similar in TLR4 KO cells to that in the wild type, which is consistent with the human data. These findings suggest that TLR2 induces an intracellular inhibitory signal to downstream pathways that elicit cytokine production, such as the TLR9 pathway. Indeed, this anti-inflammatory role of TLR2 has been demonstrated before, both in *vitro* and in *vivo* (1, 9, 35, 36). Moreover, TLR2 has also been implicated in the induction of regulatory T-cell responses, further emphasizing the immunosuppressive potential of TLR2 signaling (27, 28, 41). Also, a *Bifidobacterium* strain has been shown to be able to induce T-regulatory cells (23). However, it remains to be elucidated whether TLR2 is involved in this process, although previously an immunoregulatory role of TLR2 in recognition of probiotic strains was indeed described (15, 17, 48).

When considering the potential therapeutic applications of these probiotic strains, one could draw useful information from the *in vitro* features of these strains. The data presented here suggest that *B. breve* may be more suitable than Lactobacilli in the context of inflammatory bowel diseases (and especially Crohn’s disease), based on its lower inflammatory potential. Th1 responses, as reflected by IFN-γ production, are poorly induced by *B. breve*, while they are known to be crucial for the pathogenesis of Crohn’s disease (24, 29). Beneficial effects of the inhibition of IFN-γ production by *B. breve*, compared to, e.g., anti-TNF-α treatment, may result in a tolerant state with decreased Th1 immune responses in the gut, whereas other (e.g., IL-1β- and TNF-α-driven) immune pathways remain intact, thereby sustaining immunocompetence of the host. However, further *in vivo* studies need to be performed to confirm these findings and to assess the effect on relevant animal models, such as experimental colitis.

In conclusion, the observed differences in the capacity to induce cytokine secretion in human primary immune cells between the *Bifidobacterium* and *Lactobacillus* strains is most likely due to the differential recognition by TLRs. TLR9 mediates proinflammatory signals induced by *B. breve*, *L. rham-
mous, and L. casei. In contrast, TLR2 exerts inhibitory effects upon recognition of B. breve but not lactobacilli. It is to be hoped that these data would contribute to the decision for a deliberate choice on what probiotic to use in a given application.

ACKNOWLEDGMENTS

This study was performed within the framework of the Dutch Top Institute Pharma DI-101. M.G.N. was supported by a Vici grant from the Netherlands Organization for Scientific Research (NWO).

We thank Jan Knol and the microbiology team for their input and supply of probiotics.

REFERENCES