INTRODUCTION

The commensal microbiota is required for optimal host development and for ongoing intestinal homeostasis, which involves an interdependence between microbes and immunity.1–3 This requires discriminative responses to commensals in comparison with pathogens to ensure tolerance and protective immunity, respectively. A characteristic feature of mucosal tolerance is the induction and expansion of Foxp3 T regulatory cells, which limit excessive proinflammatory responses.4–5 We and others have identified specific microbes, which selectively promote Foxp3 polarisation within the mucosa of mice.6–10 In addition, recent studies in patients with inflammatory diseases (ulcerative colitis and allergy) suggest that feeding with specific therapeutic microbes can increase the proportion of CD25high T cells.11–12 However, the in vivo mechanisms underpinning the microbiota-associated features of tolerance within the gastrointestinal mucosa.
influence on T regulatory cells are not well understood and it is not clear whether the mechanistic results obtained in the murine system are also applicable to humans.

Within the gastrointestinal mucosa, a number of cell types including epithelial cells, intraepithelial lymphocytes, lamina propria macrophages and dendritic cells are required to maintain intestinal homoeostasis and tolerance. In particular, both myeloid (mDCs) and plasmacytoid dendritic cells (pDCs) are in close contact with microbes and are responsible for presenting microbial and dietary antigens to the adaptive immune system, thereby influencing polarisation of the adaptive response via cytokine and metabolite production. Thus, the decision to induce Foxp3+ T cells is significantly influenced by activation of DC pattern-recognition receptors (PRRs), which programme DC gene expression and subsequent T cell polarisation. Coordination between PRR signalling pathways is important for the induction of the appropriate DC and T cell response. For example, Toll-like receptor-2 (TLR-2) recognition of zymosan results in the secretion of retinoic acid and interleukin (IL)-17 induction. In addition, TLR-2 activation was shown to inhibit TLR-3-associated inflammatory responses within the skin in a TRAF-1-dependent mechanism. Furthermore, DC subsets may use different molecular mechanisms to cooperate in the induction of T regulatory cells.

**Bifidobacterium longum** subspecies *infantis* 55624 (*B. infantis*) is a commensal microbe originally isolated from the human gastrointestinal mucosa and has been extensively studied for its ability to regulate inflammatory responses, both in mice and humans. We selected this bacterium as a likely candidate for the ability to induce Foxp3+ T regulatory cells in humans. Our results demonstrate that significantly elevated IL-10 responses and Foxp3 expression occur in humans after in vivo exposure to *B. infantis* by oral consumption. In addition, we provide evidence for the potential cellular and molecular mechanisms underpinning this regulatory effect as both human mDCs and pDCs specifically induce Foxp3+CD4+ cells following in vitro incubation with *B. infantis*. However, the mechanisms of Foxp3 induction differ for mDCs and pDCs. Induction of Foxp3+ T cells by mDCs is TLR-2-, DC-SIGN- and retinoic acid-dependent, whereas induction of Foxp3 cells by pDCs requires indoleamine 2,3-dioxygenase (IDO).

### MATERIALS AND METHODS

#### Human studies

Two healthy human volunteer studies were performed and both were approved by the clinical research ethics committee of the Cork Teaching Hospitals, Ireland. Each potentially eligible healthy adult volunteer was evaluated by a full clinical history and physical examination, haematological and serum chemistry analysis. Clinically significant findings in any of the evaluation parameters led to the exclusion of that volunteer. In the first study, healthy adults were randomised to receive *B. infantis* (n=10; 1×10^7 live bacteria per day) or placebo (n=12; cryoprotect with no bacteria) for 8 weeks. All investigators, as well as the volunteers, remained blinded to the randomisation process until completion of the study. The second study was conducted with healthy adults fulfilling the same selection criteria as outlined above but in this study all subjects were fed *B. infantis* (n=17; 1×10^7 live bacteria per day) for 8 weeks.

Peripheral blood mononuclear cells (PBMCs) were isolated on day −1 (before feeding) and day 56 (after feeding). Freshly isolated PBMCs were stained with monoclonal antibodies to CD4-PerCP, CD25-APC, ICOS-PE, CTLA-4-PE and Foxp3-Alexa Fluor 488 (Ebioscience, San Diego, California, USA). Duplicate samples were evaluated using a FACS Calibur (Becton Dickinson, Oxford, England) and analysis was carried out using the BD CellQuest software. In addition, 1×10^6 cells/ml PBMCs were stimulated with anti-CD3 (5 μg/ml) and anti-CD28 (5 μg/ml) antibodies for 48 h. PBMC supernatants were analysed for cytokine levels simultaneously using the MesoScale Discovery multiplex platform.

#### Bacterial labelling and visualisation of cell binding

*B. infantis* was stained with carboxyfluorescein diacetate, carboxyfluorescein succinimidyl ester (CFSE) (Invitrogen) while MDDCs were co-stained with anti-CD11c PE-Cy5 (BD Pharmingen, Franklin Lakes, USA). MDDCs were visualised at multiple time points using multiparametric imaging flow cytometry ImageStream X (Amnis Corporation, Seattle, USA) and images were analysed using IDEAS software (Amnis Corporation). CD80 FITC and CD86 PE (BD Pharmingen) expression was evaluated by flow cytometry (Gallios system, Beckman Coulter, Brea, USA) and IgG2B control antibody (R&D Systems Europe, Abingdon, UK). Cytokine secretion was quantified by Bio-Plex multiplex suspension array (Bio-Rad Laboratories, Hercules, USA).

#### Dendritic cell isolation and culture conditions

Dendritic cell experiments were performed using cells isolated from naïve (ie, non-*B. infantis* fed) healthy volunteers. Human peripheral blood monocytes were obtained using CD14 positive isolation with the MACS system (Miltenyi Biotec, Bergisch Gladbach, Germany). Cells were cultured in cRPMI medium (Invitrogen, Carlsbad, USA) with 1000 U/ml IL-4 (Novartis, Basel, Switzerland) and 1000 U/ml granulocyte-macrophage colony-stimulating factor (PeproTech, London, UK) for 5 days in order to generate monocyte-derived dendritic cells (MDDCs). Peripheral blood mDCs were isolated following CD5, CD14 and CD19 depletion and CD1c positive selection with the MACS system. Peripheral blood pDCs were positively enriched using CD31404 isolating the MACS system. In addition, flow cytometric sorting with anti-CD123 FITC (Miltenyi Biotec) yielded a highly purified pDC population. Peripheral blood CD4 T cells were isolated by negative selection with the MACS system. MDDCs, mDCs and pDCs were routinely cultured in cRPMI medium and stimulated with bacterial strains or remained unstimulated. For blocking experiments, dendritic cells were preincubated for 30 min with control oligonucleotide GCTAGATTTACCGT, TLR9 antagonist oligonucleotide TTTAGGTCTAGATTAGTTTCGG (Microsynth, Balgach, Switzerland) or the blocking monomeric antibodies: anti-TLR2 (gift from C Kirschning, Munich, Germany), anti-DC-SIGN (AZDN1, Beckman Coulter, Brea, USA) and IgG2B control antibody (R&D Systems Europe, Abingdon, UK). Cytokine secretion was quantified by Bio-Plex multiplex suspension array (Bio-Rad Laboratories, Hercules, USA).

#### RALDH assessment

MDDCs, mDCs and pDCs were stimulated with bacteria (with or without inhibitors) for 16–24 h in cRPMI. RALDH activity was determined using the ALDEFLOUR kit (Aldagen, Durham, USA) and positive cells were visualised by flow cytometry. In representative experiments, MDDCs were incubated with PKH26-stained *B. infantis* in order to co-localise bacterial binding and RALDH induction.
HEK-293 TLR-2 cells
HEK-Blue hTLR-2 cells and HEK-Blue Null1 cells (Invivogen, San Diego, USA) were stimulated with *B. infantis* for 24 h. Both cell lines express the NF-κB-inducible secreted embryonic alkaline phosphatase reporter. The TLR-2 ligand Pam3CSK4 (2.5 μg/ml, Calbiochem, Merck KGaA, Darmstadt, Germany) was used as a positive control.

Dendritic cell T cell co-cultures
Dendritic cells were stimulated for 4 h with test bacterial strains and co-cultured with autologous CD4 T cells at a 1:40 ratio (mDCs) or a 1:20 ratio (MDDCs and pDCs) in AIM-V media (Invitrogen). After 5 days, cells were re-stimulated with anti-CD28 (generated in house), anti-CD3 (Orthoclone OKT3, Janssen-Cilag) and anti-CD2 (Sanquin, Amsterdam, Netherlands). Two days later lymphocytes were permeabilised and stained for CD4, CD25 and Foxp3 (eBioscience). Citral (Sigma-Aldrich, St Louis, USA), LE135 (Tocris Bioscience, Bristol, UK) and 1-methyl-L-tryptophan (Sigma-Aldrich) were added as RALDH2 and IDO inhibitors, respectively.

Statistical analysis
Wilcoxon matched-pairs test or Student t test were used to evaluate the effect of inhibitors on in vitro activated dendritic cells and dendritic cell–T cell co-cultures. In addition, D’Agostino and Pearson normality tests were performed on the cytokine and flow cytometric data from the human volunteer studies. Measurements before and after feeding were assessed using the Student t test for paired data while comparisons between placebo and treatment groups were performed using a Student t test (two-tailed) and Mann–Whitney test. All data analysis was carried out using GraphPad Prism software.

RESULTS
Feeding of healthy human volunteers with *B. infantis* is associated with induction of IL-10 and Foxp3 in vivo
Healthy human volunteers were fed *B. infantis* or placebo for 8 weeks. PBMCs were isolated before and after the feeding period. *B. infantis* feeding was associated with significantly enhanced IL-10 levels in anti-CD3/CD28 stimulated PBMCs. Figure 1: *Bifidobacterium infantis* feeding in healthy humans is associated with increased secretion of interleukin (IL)-10. (A). In vitro stimulated peripheral blood mononuclear cells displayed increased secretion of IL-10 following *B. infantis* oral intake (n=10; p=0.01) for 8 weeks which was not seen in the placebo group (n=12; p=0.64). (B). The increased secretion of IL-10 in healthy human volunteers following *B. infantis* feeding was repeated in a second study (n=17). (C). While in vitro anti-CD3/CD28-stimulated peripheral blood mononuclear cells from *B. infantis*-fed volunteers displayed increased secretion of IL-10 (p<0.001), there was no change in IL-2 (p=0.33), IL-12p70 (p=0.26), tumour necrosis factor (TNFα) (p=0.42) or interferon (IFN)γ (p=0.56) secretion. *p<0.05 versus placebo; *1 p<0.01 versus pretreatment (week 0).

Gut microbiota

![Bifidobacterium infantis feeding in healthy humans](http://gut.bmj.com/). Gut: first published as 10.1136/gutjnl-2011-300936 on 3 November 2011. Downloaded from http://gut.bmj.com/ on January 11, 2024 by guest. Protected by copyright.
(p=0.01), while IL-10 levels in the placebo group did not change (p=0.64; figure 1A). We performed a second study with greater numbers of healthy human volunteers, in which we reassessed PBMC IL-10 levels as before and in addition, we quantified Foxp3 expression. We again observed the same increase in anti-CD3/CD28 stimulated PBMC secretion of IL-10 (p<0.001; figure 1B), while we observed no difference in anti-CD3/CD28 stimulated IL-2, IL-12p70, tumour necrosis factor (TNF)α or interferon (IFN)γ secretion (figure 1C). In addition, the percentage of peripheral blood CD4 T cells that express Foxp3 increased in CD25high and CD25intermediate CD4 T cells, but not CD25negative CD4+ T cells, following B infantis feeding. *p<0.01 versus pretreatment (week 0).

Figure 2 Bifidobacterium infantis feeding in healthy humans is associated with increased expression of Foxp3. Foxp3 expression was significantly increased in CD25high and CD25intermediate CD4 T cells, but not CD25negative CD4+ T cells, following B infantis feeding. *p<0.01 versus pretreatment (week 0).
was significantly increased following *B. infantis* feeding (week 0 CD4+Foxp3+ cells =8.14±0.25% vs week 8 CD4+Foxp3+ cells =9.19±0.34%, p=0.003). The increased expression of Foxp3 was seen in the CD25^high^ and CD25^intermediate^ CD4 T cells, but not in the CD25^-^ T cells (figure 2). The CD4+CD25+Foxp3+ cells displayed a more pronounced regulatory phenotype after *B. infantis* administration as inducible T-cell costimulator (ICOS) was expressed by significantly more of these cells at week 8 (figure 3). Cytotoxic T-lymphocyte antigen 4 (CTLA-4) expression also increased but the difference did not reach statistical significance (figure 3, p=0.06).

**B. infantis** induces DC maturation and regulatory activity

In order to understand how *B. infantis* induced IL-10 polarisation and expression of Foxp3 cells in humans, we focused on DCs as the potential cellular mediators, which could acquire *B. infantis* in vivo within the mucosa and secrete immunoregulatory factors that induce T cell polarisation. Human MDDCs, directly isolated human mDCs and directly isolated human pDCs were shown, in vitro, to bind *B. infantis* (figure 4A,B). In addition, MDDCs were able to internalise this microbe (figure 4C). A dose-dependent maturation of MDDCs was evident from the increased expression of CD80 and CD86 (figure 4D). A similar increase in myeloid dendritic cell (mDC) costimulatory molecule expression was seen (results not shown).

*B. infantis* stimulated MDDCs, mDCs and pDCs secreted IL-10, but not IL-12p70, in response to this bacterium (figure 5A-C). This was not seen with all *Bifidobacteria* as MDDCs secreted IL-12p70, when co-incubated with other unrelated *Bifidobacterial* strains and pathogenic bacteria such as...
Streptococcus pyogenes, Staphylococcus aureus and Pseudomonas aeruginosa (supplementary figure S1). In addition to regulatory cytokines, B infantis induced expression of the ALDH1A2 gene, which encodes for the enzyme retinaldehyde dehydrogenase 2 (RALDH2), in MDDCs and mDCs but not pDCs (figure 5D). ALDH1A2 was induced quickly in MDDCs, while ALDH1A2 was induced at later time points in mDCs. B infantis did not alter ALDH1A1 or ALDH1A3 gene expression in any DC subset (results not shown). The functional activity of RALDH2 was confirmed in MDDCs and mDCs by flow cytometry (figure 5E). Inhibition of RALDH activity with diethylaminobenzaldehyde completely blocked the detection of BODIPY-aminoacetate-positive cells. However, pDCs did not upregulate RALDH activity with B infantis incubation (figure 5E). MDDCs which had bound B infantis, expressed a higher level of RALDH metabolic activity that MDDCs that had not captured B infantis (supplementary figure S2A,B). In addition, the induction of RALDH was dose dependent and the optimal dose of approximately 5×10⁶ bacterial cells (10:1 bacteria:MDDC cell number) was used in subsequent experiments (supplementary figure S2C). Another metabolic enzyme with regulatory activity is IDO. B infantis induced IDO gene expression in MDDCs, mDCs and pDCs, with relatively higher levels of expression by pDCs (figure 5F). The kinetics of IDO induction was different for each DC subset. Expression of MDDCs slowly increased over time, while mDCs reached maximal expression levels at 6 h and expression was maintained over time. Similarly, expression of pDCs IDO peaked at 6 h but decreased rapidly thereafter.

The induction of ALDH1A2 in MDDCs by B infantis 35624 was not seen with the other Bifidobacterial strains that were examined (supplementary figure S3A), while IDO gene expression was enhanced by lipopolysaccharide and all three Bifidobacterial strains (supplementary figure S3B).
Figure 5  *Bifidobacterium infantis* induces a regulatory dendritic cell phenotype. IL-10 secretion by monocyte-derived dendritic cells (MDDCs) in response to *B infantis* increased in a dose-dependent manner, while interleukin (IL)-12p70 levels remained low (A; mean±SE, n=5 donors). Similarly, directly isolated myeloid DCs (mDCs) B; n=3 donors) and plasmacytoid DCs (pDCs) C; n=3 donors) secreted IL-10, but not IL-12p70 in response to *B infantis*. (D) *ALDH1A2* gene expression (encoding the retinaldehyde dehydrogenase 2 (RALDH2) enzyme) was quantified every 6 h, until 18 h, after *B infantis* stimulation of MDDCs, mDCs and pDCs. (E) The functional activity of RALDH was determined by detection of BODIPY-aminoacetate (BAA)-positive MDDCs and mDCs, but not pDCs, exposed to *B infantis* for 24 h. The RALDH inhibitor diethylaminobenzaldehyde (DEAB) blocked the conversion of the substrate. Gene expression of the metabolic enzyme indoleamine 2,3-dioxygenase (IDO) was seen in MDDCs, mDCs and pDC (F). (D–F) All experiments were repeated independently for at least four donors.
**B infantis** activation of DCs is PRR dependent

In order to better understand the molecular basis for **B infantis**-induced DC immunoregulatory responses, we next examined the role played by a range of PRRs. MDDCs express high levels of Dectin-1; however, no significant differences in cytokine production were seen for IL-10 (1626 ± 645 pg/ml vs 1522 ± 418 pg/ml) or IL-12p70 (12.5 ± 4.8 pg/ml vs 11.9 ± 4.1 pg/ml) secretion with Dectin-1 inhibition. Blockade of MDDC TLR-2 resulted in significantly decreased secretion of IL-10 and significantly increased secretion of IL-12p70 and TNFα (figure 6A). Inhibition of MDDC DC-SIGN did not significantly alter IL-10 or IL-12 secretion, although TNFα secretion was significantly increased (figure 6A). Blockade of mDC TLR-2 or DC-SIGN resulted in significantly reduced IL-10 secretion associated with increased secretion of TNFα (figure 6B). In order to confirm that TLR-2 induced an intracellular signalling cascade in response to **B infantis**, we examined HEK-293 cells, which were engineered to express TLR-2. HEK-293^TLR-2^ cells responded to **B infantis** as demonstrated by an increase in NF-κB activation and IL-8 secretion (supplementary figure S4). In contrast, NF-κB activation and IL-8 secretion did not increase over baseline levels in HEK^TLR-2^ cells. In addition, preincubation of HEK-293^TLR-2^ cells with anti-TLR-2 blocking antibody significantly reduced NF-κB activation and IL-8 secretion in response to **B infantis**. TLR-2 can form heterodimers with either TLR-1 or TLR-6. Blocking TLR-1 had no effect on **B infantis**-induced NF-κB activation or IL-10 secretion, while TLR-6 had a partial effect but not as significant as TLR-2 blockade (supplementary figure S5). The combination of anti-TLR-2 and anti-TLR-6 antibodies was the most effective in the inhibition of HEK-293 NF-κB activation and MDDC IL-10 secretion. TLR-2 was expressed by pDCs at a very low level and...
blocking experiments did not alter the pDC IL-10 response to *B. infantis* (figure 6C), while IL-12p70 was not detected. However, blockade of TLR-9 with an inhibitory oligonucleotide abolished the secretion of IL-10 by pDCs in response to *B. infantis* (figure 6D). In order to evaluate if pDCs respond in a similar manner to specific TLR-9 agonists, pDCs were stimulated with CpG or *B. infantis*. Both *B. infantis* and CpG stimulation resulted in enhanced IL-10 and IDO gene expression, while IFNα gene expression was only increased after CpG stimulation (figure 6E). MDDCs and mDCs express very low levels of TLR-9 and TLR-9 inhibitory oligonucleotides did not alter the MDDC response to *B. infantis* (results not shown).

In addition to cytokine production, the blocking of MDDC TLR-2 or DC-SIGN resulted in significant inhibition of retinoic acid metabolism in *B. infantis*-stimulated MDDCs and mDCs (figure 7A,B). Furthermore, specific activation of MDDC TLR-2 by Pam3CSK4 induced retinoic acid metabolism, while stimulation of DC-SIGN by mannosylated lipoarabinomannan (ManLam) marginally increased retinoic acid metabolism (figure 7C). In contrast, specific activation of TLR-4 or TLR-5 by lipopolysaccharide or flagellin, respectively, did not induce retinoic acid metabolism in MDDCs (figure 7C).

### B. infantis-stimulated DCs induce Foxp3 T cells

As human DCs clearly secrete immunoregulatory mediators in response to *B. infantis*, we assessed whether these DCs could also induce Foxp3 expression by autologous T cells in vitro. MDDCs were incubated with *B. infantis* for 4 h, washed and re-incubated with autologous CD4 cells for 5, 7 or 9 days. Peak induction of Foxp3, compared with unstimulated MDDCs was seen at 7 days with or without costimulation (supplementary figure S6A). In all subsequent experiments, DCs were co-cultured for 7 days with autologous CD4 T cells for assessment of Foxp3 induction. After incubation with *B. infantis*, MDDCs, mDCs and pDCs induced Foxp3 expression in cultures with CD4 T cells (figure 8A). In addition, enhanced IL-10 secretion was seen in the *B. infantis*-stimulated DC–T cell co-cultures, compared with T cells incubated with unstimulated DCs (figure 8B). Blocking TLR-2 significantly reduced IL-10 secretion from MDDC and mDC–T cell co-cultures, with no effect on pDC–T cell IL-10 secretion (figure 8C), while blocking TLR-9 significantly reduced pDC–T cell secretion of IL-10 (figure 8D).

In order to determine which PRRs were responsible for the preferential induction of Foxp3 T cells, MDDCs were preincubated with anti-TLR-2 or anti-DC-SIGN blocking antibodies before *B. infantis* activation. A significant reduction in the CD4 +CD25+Foxp3+ population was seen when dendritic cell TLR-2 responses were blocked. To a lesser extent, blockade of DC-SIGN also significantly reduced CD4+CD25+Foxp3+ induction (figure 9A). No induction of T-bet or GATA-3 positive T cells over baseline was seen. However, incubation of MDDCs with other *Bifidobacteria*, which induced IL-12p70 secretion from dendritic cells, resulted in the induction of T-bet+T cells (supplementary figure S6B). RALDH2 induction has been associated with the enhanced capacity of mucosal associated CD103+ dendritic cells to induce Foxp3 T cells. After inhibition of MDDC or mDC retinoic acid synthesis (using citral) or inhibition of T cell retinoic acid receptor signalling (using LE135), the induction of Foxp3 T cells by *B. infantis*-stimulated MDDCs and mDCs was suppressed (figure 9B). Using the IDO inhibitor 1-methyl tryptophan, induction of Foxp3 T cells by *B. infantis*-stimulated pDCs was inhibited (figure 9C). *B. infantis*-stimulated MDDC induction of Foxp3 T cells was also partially reduced in the presence of 1-methyl tryptophan; however, the reduction was not statistically significant and not as substantial as that seen for pDC–T cells (figure 9D).

### DISCUSSION

Induction of Foxp3 T regulatory cells is a pivotal feature of mucosal immune tolerance. In this study, we showed that oral feeding of healthy human volunteers with *B. infantis* results in increased numbers of Foxp3+CD4+ T cells within peripheral blood, which is associated with enhanced secretion of IL-10 following stimulation. In addition, our in vitro data support the hypothesis that DCs are responsible for the induction of Foxp3 cells. Both mDC and pDC subsets play a role, but recognise *B. infantis* via different PRRs. Induction of Foxp3 T cells by MDDCs and mDCs involves TLR-2, DC-SIGN and retinoic
acid metabolism. However, induction of Foxp3 T cells by pDCs is independent of TLR-2 and retinoic acid but requires IDO. To our knowledge this is the first report which demonstrates that human DC subsets use different pathways when exposed to a commensal microbe that enhances Foxp3 expression in autologous CD4 T lymphocytes.
Human Foxp3 T cells are heterogeneous in phenotype and function, composing distinct, although related, subpopulations. Interestingly, enhanced expression of ICOS and CTLA-4 within the Foxp3 population suggests that *B. infantis* induces an effector Treg phenotype. B. infantis feeding was associated with increased numbers of CD25 cells that expressed Foxp3 but there was no effect on Foxp3 expression within the CD25+ population. One possible explanation is that Foxp3 can promote CD25 expression, and therefore *B. infantis*-associated induction of Foxp3 in CD25+ cells leads to the expression of CD25 and their inclusion in the CD25 gate. Alternatively, *B. infantis* might not induce new CD25+Foxp3+ cells in vivo, but rather *B. infantis* might stabilise and promote expansion of the pre-existing CD25+Foxp3+ population.

The default status of the gastrointestinal microenvironment is thought to favour induction of regulatory lymphocytes. For example, retinoic acid generation from vitamin A occurs in intestinal epithelial cells and specialised DC subsets, resulting in the conversion of naïve T cells into Foxp3 T regulatory cells. However, the gut-specific factors which promote vitamin A metabolism have been poorly described. We describe upregulation of the retinoic acid metabolising enzyme RALDH2 in mDCs, which are exposed to a single commensal strain. The retinoic acid response is functional and contributes to the induction of Foxp3 cells by *B. infantis*-stimulated mDCs and myeloid DCs (mDCs; n=3 donors). In addition, inhibition of pDC IDO activity by 1-methyl tryptophan significantly attenuated the plasmacytoid DC (pDC) induction of Foxp3 T cells. (D) IDO inhibition partially reduced *B. infantis*-stimulated mDC-T cell Foxp3 induction (n=3 donors) but not as significantly as IDO inhibition for pDC-T cell Foxp3 induction (n=5 donors). *p<0.05 versus unstimulated cells.

Figure 9  Toll-like receptor-2 (TLR-2), DC-SIGN, retinaldehyde dehydrogenase 2 (RALDH2) and indoleamine 2,3-dioxygenase (IDO) are required for optimal induction of Foxp3 T cells. (A) Induction of Foxp3 T cells by *Bifidobacterium infantis* was blocked when monocyte-derived dendritic cells (MDDCs) were preincubated with anti-TLR-2 or anti-DC-SIGN blocking antibodies. In contrast, there was no effect on T-bet or GATA-3 expression by T cells (mean±SE, n=4 donors). (B) Inhibition of retinoic acid production (citral) or retinoic acid signalling (LE135) blocked the induction of Foxp3 cells by *B. infantis*-stimulated MDDCs and myeloid DCs (mDCs; n=3 donors). (C) In addition, inhibition of pDC IDO activity by 1-methyl tryptophan significantly attenuated the plasmacytoid DC (pDC) induction of Foxp3 T cells. (D) IDO inhibition partially reduced *B. infantis*-stimulated MDDC-T cell Foxp3 induction (n=3 donors) but not as significantly as IDO inhibition for pDC-T cell Foxp3 induction (n=5 donors). *p<0.05 versus unstimulated cells.
short-chain fatty acids suggest that we may have previously underestimated the importance of the relationship between diet and the microbiota. In addition, acetate production (following carbohydrate fermentation) by certain Bifidobacteria strains mediates protection from lethal Escherichia coli infection in mice. Recent findings on the role of PRR signalling in mucosal homeostasis have emphasized the delicate balance between different PRR functions, and shown that defective PRR signalling can result in inflammation. TLR-2 KO animals are more sensitive to dextran sulphate-induced colitis, while TLR-2 gene variants are associated with disease phenotype in patients with inflammatory bowel disease. Indeed, TLR-2 has been shown to promote Foxp3 expression in response to intestinal microbes in murine models. Our results show that inhibition of human mDC TLR-2/6 activation suppressed IL-10 secretion and Foxp3 induction, while enhancing secretion of IL-12p70 and TNFα following B infantis exposure. DC-SIGN activation by B infantis is required for full RALDH activity, and blocking DC-SIGN results in significantly fewer Foxp3+ T+ CD4+ T cells. Similarly, TLR-9 is required for pDC secretion of IL-10 in response to B infantis. However, CpG stimulation of pDCs resulted in enhanced IFNα gene expression, which was not seen with B infantis stimulation, suggesting that other molecular pathways distinct from those induced solely by TLR-9 are involved in the pDC response to this bacterium. These findings suggest that cross-talk between TLR-2/6, DC-SIGN and TLR-9 and other PRRs determines the innate and subsequent adaptive immune response to this commensal microbe. Appropriate PRR activation in vivo may promote immune homeostatic mechanisms, which limit the activation of proinflammatory responses and protect mucosal tissue from injury. In addition, the involvement of multiple PRRs suggests that multiple bacterial components including lipoteichoic acids (TLR-2), polysaccharides (DC-SIGN) and DNA (TLR-9) are all important for optimal induction of the immune regulatory programme in vivo. Furthermore, a communal microbe that expresses all of these regulatory factors may be more efficient in the local induction of Foxp3+ cells than a commensal bacterium that only expresses one or two regulatory factors.

Both mDCs and pDCs are present within the gastrointestinal tract in relatively high numbers compared with the peripheral blood. In the mouse, pDCs are numerically dominant within the lamina propria and Peyer’s patches, while mDCs dominate in mesenteric lymph nodes. In murine models, pDCs have been shown to be essential for the induction and maintenance of oral tolerance as systemic depletion of pDCs prevents tolerance induction to fed antigen, while adoptive transfer of oral antigen-loaded liver pDCs induced antigen-specific suppression of CD4 and CD8 T cell responses. It is likely that mDCs and pDCs will also cooperate in the induction of tolerance to communal microbes other than B infantis, but our data suggest that not all Bifidobacteria induce the same pDC and mDC response.

B infantis 35624 has been shown to protect against inflammatory disease in a number of murine models (including colitis, arthritis, respiratory allergy and infectious models). In humans, we now demonstrate in vivo that oral administration of this bacterium results in elevated IL-10 responses and Foxp3 expression in CD4 T cells and we describe the potential cellular mechanisms underpinning this regulatory response. Manipulation of T regulatory cell numbers or functions is an exciting therapeutic target in a wide range of inflammatory diseases. A clearer understanding of the mechanisms employed in vivo for the induction of oral tolerance by the microbiota will probably result in rational strategies to manipulate both effector and regulatory T cells, thereby influencing gastrointestinal disorders such as food allergy, eosinophilic oesophagitis, irritable bowel syndrome and inflammatory bowel diseases.

**Funding**  The authors are supported by Swiss National Foundation grants (project numbers 320030-123099 and 310030-127356), Christine Kühne Center for Allergy Research and Education, Science Foundation Ireland and Alimentary Health Ltd.

**Competing interests**  DG and BK are employees of the university campus company Alimentary Health Ltd. LOM, FS and EQ are consultants to Alimentary Health Ltd. FS has received research grants from GSK. CA has received research support from Novartis and Stallergenes and consulted for Actelion, Aventis and Allergopharma. PK, MZ, RF and RFer have no conflict of interest. The content of this article was neither influenced nor constrained by these facts.

**Ethics approval**  Clinical research ethics committee of the Cork Teaching Hospitals, Ireland.

**Contributors**  PK, DG, MZ, RFre, RFerstl and LOM performed the laboratory analysis and contributed to the interpretation of the data. FS, EQ, BK, CA and LOM contributed to study concept and design, analysis and interpretation of the data and drafting of the manuscript while LOM supervised the conduct of these studies.

**Provenance and peer review**  Not commissioned; externally peer reviewed.

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