ORIGINAL ARTICLE

Probiotic and postbiotic activity in health and disease: comparison on a novel polarised ex-vivo organ culture model

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ABSTRACT

Background and aims Probiotics and their metabolic products, here called postbiotics, have been proposed as food supplements for a healthier intestinal homeostasis, but also as therapeutic aids in inflammatory bowel disease (IBD) with, however, very little clinical benefit. This may be due to the lack of reliable preclinical models for testing the efficacy of different strains.

Methods The activity of three probiotic strains of Lactobacillus (or a postbiotic) was analysed and compared with a pathogenic strain of Salmonella on a novel organ culture system of human healthy and IBD intestinal mucosa developed in our laboratory. The system maintains an apical to basolateral polarity during stimulation due to the presence of a glued cave cylinder. The cylinder is detached at the end of the experiment and the tissue is processed for histology and immunohistochemistry. Cytokines released from the basolateral side are analysed.

Results The model system provides several physiological characteristics typical of a mucosal microenvironment including the presence of an organised mucus layer and an apical to basolateral polarity. Polarised administration of bacteria is critical to control the ensuing immune response as it mimics the physiological entrance of bacteria. The authors show that probiotics are not always beneficial for the healthy host and can also be detrimental in inflamed IBD. This study shows that a potent postbiotic can protect against the inflammatory properties of invasive Salmonella on healthy tissue and also downregulate ongoing inflammatory processes in IBD tissue.

Conclusions Probiotics can have inflammatory activities in both healthy and IBD tissue. Valid preclinical data on proper model systems should therefore be obtained before specific probiotic strains enter the clinics, especially if administered during acute inflammatory responses. Postbiotics may be a safe alternative for the treatment of patients with IBD in the acute inflammatory phase.

BACKGROUND

The importance of a balanced nutrition and a healthy intestine for the well-being of humans has been known for many years. The intestinal mucosa, a vast surface of 200 m², is the part of our body devoted to nutrient absorption and responsible for taking full advantage of what we ingest. This function is carried out with the help of resident commensal microorganisms (microbiota) that...
Probiotics participate in the degradation of complex macromolecules. The microbiota co-exists harmoniously with its host, offering and acquiring many benefits. Hence, the gut mucosa is continuously challenged with microbial antigenic stimulation from normal intestinal flora and does not mount an immune reaction against it; however, it is still able to react to pathogenic bacteria. Dysregulation of the composition of the microbiota has recently been suggested as a possible risk factor leading to inflammatory bowel disease (IBD) in genetically susceptible individuals.

IBD comprises two pathological conditions affecting the bowel—ulcerative colitis (UC) and Crohn’s disease (CD). It is characterised by excessive inflammation in various parts of the intestinal wall, eventually leading to mucosal damage, ulcers and fibrosis. Even though the pathogenesis of IBD is still unknown, current theories hypothesise that a dysregulated immune reaction against components of the normal luminal flora is a major driver to IBD-related mucosal inflammation. Indeed, several studies have documented an altered gut flora composition in individuals with CD and UC. For instance, a reduction in Faecalibacterium prausnitzii in the normal gut microbiota has been associated with recurrence of CD. Whether this represents a primary event responsible for IBD-related intestinal inflammation or a consequence of the IBD-related inflammatory milieu is still a matter of debate.

Even if there is no definitive cure for IBD, currently available treatments for patients with UC and CD include aminosalicylates, steroids and immunosuppressive drugs such as thiopurines and anti-tumour necrosis factor (TNF) agents aimed at controlling mucosal inflammation. However, these treatments are beneficial only in a proportion of patients with IBD and surgery often remains the best therapeutic option.

Probiotics are living microorganisms which, when administered in adequate amounts, confer a health benefit on the host. The health benefits of probiotics are highly dependent on the bacterial strain and on the clinical setting in which they are used. Each probiotic species, and within each species each strain, may have distinct activities. Recent clinical studies have concluded that caution needs to be taken when administering probiotics in patients with acute inflammation. Indeed, treatment with a mixture of probiotics in patients with acute pancreatitis resulted in death in 16% of the patients in the probiotics group compared with 6% in the placebo group.

Thus, before taking probiotics into the clinic, thorough preclinical studies have to be carried out.

We describe a human mucosa explant culture model in which an apical to basolateral polarity is preserved during stimulation with bacteria. With this model system we tested the activity of different probiotics on healthy and IBD tissues.

**METHODS**

Tissue sampling, bacteria culture, histochemistry, gentamicin protection assays, cytokine secretion measurement and statistical analysis are shown in the online supplement.

**Tissue culture and stimulation**

Once in the laboratory, the clean mucosal layer was washed in Hank’s Balanced Salt Solution buffer and cut with sterile scalpels into 1 cm² pieces. The pieces were placed on sterile metal grids and the cylinder (cloning cylinder, various sizes, BellCo, Modena, Italy) was attached with surgical glue (Vetbond, 3M, Milan, Italy) under sterile conditions with a pair of forceps (figure 1). The culture medium was Dulbecco’s Modified Eagle Medium supplemented with 15% freshly added fetal bovine serum, non-essential amino acids, sodium pyruvate, glutamine, epidermal growth factor (200 ng/ml, Peprotech, Milan, Italy) and Insulin-Transferrin-Selenium-X (10 μl/ml, Gibco, Monza, Italy). 1 ml of complete medium was dispensed in the centre well of the plate (Falcon, centre-well organ culture dish). Stimulation was performed with 4×10⁸ colony forming units (CFU)/cylinder Salmonella typhimurium in 200 μl medium with or without Lactobacillus paracasei supernatant (SN) (5%). The same number of CFUs was used for inoculation of probiotics. Dilutions of bacterial cultures were plated onto LB or MRS agar plates to confirm the

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**Figure 1** Application of a cylinder on the luminal face of an intestinal mucosal explant does not impact on tissue well-being. (A, B) Schematic representation and photographs of the technical setting for culture and apical stimulation. (C) Tissue cultured in the absence of the cylinder (left panel) and with the cylinder (right panel). Ellipse: cylinder contact point. Scale bars: 500 μm. (D) Left panel: Tissue stained with phalloidin-FITC in the interior of the cylinder (green) and 4',6-diamidino-2-phenylindole (blue, for nuclear staining) once the cylinder was removed. Middle panel: The same piece of tissue inside the cylinder (magnification 4×). Right panel: Tissue processed with two cylinders of different size (magnification 1.5×). White lines represent cylinder borders.
accuracy of the bacterial counts. As a control for the SN, (5%) unfermented bacterial medium (MRS) was added to the cylinder.

After 2 h at 37°C in a 5% carbon dioxide incubator, the medium was removed from the inside of the cylinder and the tissue was transferred to the oxygen chamber. The chamber was filled with pressurised oxygen (Vitalaire, Milan, Italy) and placed at 37°C for the remaining 22 h of culture.

RESULTS
Technical set-up of the organ culture model to achieve polarised stimulation

The interaction of bacteria with intestinal mucosa is complex and comprises several key events including attachment/degradation of mucus, competition with the commensal microbiota and resistance to antimicrobial peptides produced by the epithelial barrier.13 To meet these requirements, we developed a new model of the intestinal mucosa which resembles as closely as possible the in vivo situation by setting up a polarised organ culture system. Healthy mucosal tissue (explant) was obtained as described in the online supplement. During the transfer the tissue was preserved in buffer with or without bacteriostatic antibiotics in order to conserve the microbiota. However, in both cases the superficial part of the mucus layer was washed off, but the microbiota adhering to the remaining mucus proliferated during the overnight culture and colonised the newly produced mucus (as attested by fluorescence in situ hybridisation, see figure 1 in online supplement). In the absence of antibiotics during transfer, the commensals hyperproliferated and contaminated the basolateral culture medium (not shown). We therefore decided to transfer the tissue in buffer containing bacteriostatic antibiotics. Once in our laboratory, the mucosa was cut into pieces of about 1 cm² and placed on metal grids with the basolateral side facing downwards (figure 1A,B). The whole ensemble was then brought onto a centre-well tissue culture plate containing 1 ml of medium. At this stage only the basolateral side of the tissue was in contact with the medium (figure 1B(i)). Following previously published protocols, we compared culture in conventional incubators with culture in a 99% oxygen-saturated atmosphere and observed that both healthy and IBD tissues were only successfully cultured in the presence of oxygen (see figure 2 in online supplement).

The ability of luminal bacteria to invade the epithelium and to enter the intestinal lamina propria (LP)—a characteristic associated with pathogenic bacteria—dictates the outcome of the elicited immune response. For instance, the engagement of Toll-like receptor (TLR)-9 by bacteria-derived unmethylated CpG sequences on the apical surface of epithelial cells induces partial activation of nuclear factor-κB (NF-κB) without stimulating the release of proinflammatory cytokines.14 In contrast, basolateral engagement of TLR9 leads to a full inflammatory response which can be inhibited by preincubating the epithelium with TLR9 ligands applied on the apical side.15 This suggests that ‘sensing’ of pathogens depends on their capacity to deliver microbial components either intracellularly or to the basolateral compartment of the epithelium for engagement of pathogen recognition receptors. Thus, to mimic the ‘natural’ condition, we sought a way to maintain the apical to basolateral polarity of the tissue during the stimulation. To this end, a cave cylinder was attached to the apical side of the mucosa with surgical glue (figure 1A,B). We then evaluated the potential detrimental effects of these components (cylinder and glue) on the explants. The cylinder did not greatly affect the three-dimensional structure of the tissue (figure 1C), causing only minimal rupture effects after careful removal for immunohistochemical evalua-
TNFα was produced in much greater quantities by explants stimulated with *Salmonella* in the absence of the cylinder, regardless of the pathological conditions (figure 2B). Immunofluorescence to assess *Salmonella* localisation in the tissue after incubation for 2 h (and immediate subsequent fixation) with or without the cylinder confirmed the penetration of *Salmonella* from the non-apical side and direct contact with LP components in the absence of the cylinder whereas, where the cylinder was present, *Salmonella* had only penetrated the mucus layer apically after 2 h of stimulation (figure 2C).

**Probiotics have diverse activity on healthy and IBD tissues**

The use of probiotics in the clinic to ameliorate the symptoms of IBD has been proposed but with limited clinical outcomes. We used our newly set-up method to evaluate the response of healthy or IBD mucosa to *Lactobacillus paracasei* B21060, *Lactobacillus rhamnosus* GG (LGG) or *Lactobacillus plantarum* NCIMB8826. These probiotic strains were chosen based on a previous study in our laboratory on a complex co-culture model of epithelial cells and dendritic cells. As expected, we did not detect significant changes in the well-being of healthy tissues after inoculation of *L paracasei* or LGG (figure 3), and the cytokine secretion profile remained similar between stimulated and negative control samples (see figure 5 in online supplement). Surprisingly, however, stimulation with *L plantarum* resulted in a clear deterioration in the tissue at the end of the culture (figure 3B, right panel), with homing towards the epithelial layer of immune cells that comprise the lymphoid aggregates usually found dispersed throughout the colon below the LP (figure 3C). This reaction was observed on all three samples stimulated with *L plantarum* on which this aggregate was found on the analysed sections, while in one further sample we did not detect the lymphoid aggregate. Consistently, *L plantarum* inoculation resulted in a slight but significant upregulation of CCL4, one of the key molecules for immune cell homing to the site of inflammation. Interleukin (IL)-1β was also significantly increased after *L plantarum* but not after *L paracasei* or LGG inoculation (see figure 5 in online supplement). In contrast, when the tissues were treated with LGG and *L paracasei* in the absence of the cylinder, thus allowing the bacteria also to come into contact with the broken edges of the tissue, both strains induced an increased inflammatory response (see figure 6 in online supplement). This further confirms the necessity of the cylinder to confine the stimulation to the apical side of the mucosa for proper evaluation of the probiotic activity of the different strains tested. Interestingly, *L paracasei* did not exhibit proinflammatory properties even when allowed to penetrate basolaterally (not shown).

Contrary to these results, probiotic inoculation on IBD mucosa (4 patients with CD (2 colon and 2 ileum) and 2 patients with UC) completely altered the structure of the tissue, regardless of the strain (figure 4). This suggests that, when a tissue is already inflamed and there is probably increased permeability and translocation of otherwise non-invasive bacteria, bacteria that would normally be harmless may worsen inflammation, suggesting that caution should be taken when using probiotics in patients in the acute phase of the disease.

**L paracasei** supernatant inhibits the inflammatory potential of *Salmonella*

As mentioned above, whole bacteria can have a detrimental effect on pathological tissue. We recently showed that *L paracasei* is capable of inhibiting the inflammatory potential of dendritic...
cells and epithelial cells in complex co-culture systems in response to *S. typhimurium*, and that this capacity is not associated with the bacteria but with a soluble mediator (postbiotic) released in the culture medium. This characteristic was unique among the three tested strains (unpublished results). A postbiotic could therefore be a safer alternative to the use of whole bacteria.

We first confirmed the anti-inflammatory activity of the SN in our model system after *Salmonella* infection of healthy tissue. We measured the secretion of TNF and IL-10 (a proinflammatory and an anti-inflammatory cytokine, respectively) from the basolateral side of the sample. The tissue was processed as described above, and pieces were stimulated with either *Salmonella* (4×10⁷ CFU/explant), *Salmonella* with 5% *L. paracasei* SN, 5% SN alone or simply medium for 1–2 h in a humidified 5% CO₂ incubator. Stimulation and immune response evaluation were carried out as described above. We observed an increase in the secretion of TNF after stimulation with *Salmonella* (figure 5A). However, when SN was added together with *Salmonella* in the cylinder, this effect was abrogated (figure 5A). SN alone had little or no effect on TNF production by the tissues (see figure 7 in online supplement). However, IL-10 production, which was reduced after *Salmonella* infection, was not diminished in samples treated with *Salmonella* plus SN or SN alone (figure 5A and figure 7 in online supplement), indicating that the SN has a dramatic effect on the inflammatory potential of *Salmonella* without affecting the anti-inflammatory response of the tissue. Paralleling the production of inflammatory cytokines, histological analyses of the tissues showed that we could mimic a classic *Salmonella* infection with ulceration of the epithelium, crypt necrosis, glandular destruction and superficial atrophy (figure 5B middle panel). In addition, we observed translocation of lymphoid aggregates towards the epithelium in response to *Salmonella* (reminiscent of that observed with *L. plantarum*), and this translocation was drastically reduced when *Salmonella* was co-incubated with SN (figure 8 in online supplement). TNF production is a consequence of NF-κB activation, so we evaluated the translocation of p65 to the nucleus after *Salmonella* infection. As opposed to untreated and control samples, in the sample treated with *Salmonella*, p65 translocated to the nucleus in many of the LP components and even in epithelial cells (figure 5C, third panel). However, samples stimulated with *Salmonella* in the presence of SN only showed a slight NF-κB p65 upregulation on...
the uppermost layer of the mucosa whereas the rest of the tissue resembled control samples (figure 5C, right panel).

**L paracasei supernatant conditions the epithelium against Salmonella invasion**

We then evaluated the mechanism responsible for the reduced inflammatory response elicited by *Salmonella* in the presence of SN. We first assessed whether the SN affected *Salmonella* proliferation. We cultured *Salmonella* with or without SN and plated culture dilutions 30 min and 3 h later. The difference between the two cultures was not significant (see figure 9A in online supplement). We then evaluated whether the postbiotic affected the capacity of *Salmonella* to invade the tissue. When inoculated alone, *Salmonella* successfully penetrated the

**Figure 5** *Lactobacillus paracasei* culture supernatant (SN) counteracts *Salmonella*-induced inflammation. (A) Tumour necrosis factor (TNF) secretion (left) and interleukin 10 (IL-10) secretion (right) after 2 h of stimulation with *Salmonella* or *Salmonella* + SN and a further 22 h culture in oxygen; medium was used as a control for basal secretion measurement. Cytokines were measured by cytometric bead array; error bars represent SEM of eight samples and statistical significance was determined by the Wilcoxon test. *p*<0.05; **p**<0.01. (B) Representative tissue histologies of samples stimulated as described with either medium (left), *Salmonella* (middle) or *Salmonella* in the presence of 5% SN (right). (C) Nuclear factor-κB activation as evaluated by p65 localisation in the nucleus (dark brown) after *Salmonella* with or without SN stimulation as in (B). Scale bars: 200 μm, insets: 2 μm.
epithelium and diffused throughout the explant (figure 6A). However, in the presence of SN, *Salmonella* appeared to be unable to penetrate the deepest layers of the LP and was mostly retained in the epithelium. To quantify the capacity of *Salmonella* to invade the tissue, we performed a gentamicin protection assay on the tissue after 1.5 h of *Salmonella* stimulation with or without SN. Tissues were incubated for 1.5 h with medium plus antibiotics (gentamicin) to kill bacteria that had not entered the tissue. They were then lysed and *Salmonella* CFUs were quantified. We observed that the number of internalised bacteria was significantly lower (around 50%) in the presence of SN than when it was absent (see figure 9B in online supplement). This difference could be due to a direct action of SN on the bacteria or on the tissue. To address this issue we preincubated *Salmonella* or tissue with or without SN for 1 h. The bacteria and tissue were then extensively washed before being brought in contact for an additional hour. As shown in figure 6B, only when the tissue was conditioned with SN was *Salmonella* less invasive. Moreover, preconditioning of the tissue further affected the invasiveness of *Salmonella* as the number of recovered CFUs was much lower than when SN was incubated simultaneously with the *Salmonella* (compare figure 9B in the online supplement with figure 6B). This indicates that SN does not act on the *Salmonella* but directly on the tissue and does not need to be present at the time of infection.

*Lactobacillus paracasei* supernatant alone is sufficient to ameliorate inflammation in IBD tissues

We then evaluated the effect of SN in pathological tissues. In general, patients with CD have a basal increase in TNF expression in the tissue and anti-TNF therapy is one of the options for the treatment of CD. Incubation of SN on colon or ileal tissues from patients with CD resulted in a significant reduction in TNF production in most of the patients (figure 7A). Moreover, we also observed a significant reduction in most of the cytokines and chemokines involved in the pathology of IBD including CCL4, CCL2, interferon γ and IL23p40 on tissues incubated with SN (figure 7A). By contrast, IL-10 secretion was not significantly altered after SN treatment, suggesting that the probiotic did not interfere with the capacity of the tissue to counteract an inflammatory response. IL-17A was not significantly altered, nor were the Th2 response-related cytokines (IL-5, IL-13 and IL-4; not shown). Immunohistochemistry data for NF-κB activation were in agreement with the aforementioned results, with nuclear translocation of p65 significantly reduced on ileal CD tissues after treatment with SN (figure 7B, C, compare middle to right panel, healthy tissue was used as a negative control for NF-κB activation). As the replacement of these populations with incoming ones is not possible in this model, this would indicate that the SN is capable of downregulating the proinflammatory activity of existing leucocytes. Thus *Lactobacillus paracasei* SN seems to be a potent and safe anti-inflammatory agent with potential therapeutic use in patients with IBD.

**DISCUSSION**

Understanding how probiotics, prebiotics or postbiotics work in preclinical models that resemble the human situation can allow a ‘rational’ choice of the different strains or compounds for clinical and/or commercial use according to the pathological condition to which they are targeted. Indeed, we recently demonstrated that different *Lactobacilli* species can be classified as either immunogenic or tolerogenic. Testing of different probiotics has often been performed on isolated immune cells or peripheral blood mononuclear cells. However, particularly in the gut, the interaction of bacteria with the mucosa is an unusually complex event requiring attachment or degradation of mucus, competition with the microbiota and resistance to antimicrobial peptides. In addition, the function of immune cells is influenced by the microenvironment and this is required to preserve intestinal homeostasis. Indeed, we have shown that signals from intestinal epithelial cells can drive the differentiation of non-inflammatory dendritic cells that differ substantially from their blood-derived counterparts. On the other hand, under inflammatory conditions, new populations of immune cells are recruited at inflamed sites, such as a new subset of CD205⁺CD209⁺ LP dendritic cells that are enriched in the gut of patients with CD and share markers with macrophages like CD14 and CD68. The development of a model system that resembles the human situation is therefore of great biological significance.

![Figure 6](http://gut.bmj.com/)

**Figure 6** *Lactobacillus paracasei* culture supernatant (SN) acts on the epithelium to protect against *Salmonella* invasion. (A) Anti-*Salmonella* staining of tissues stimulated with *Salmonella* in the absence (middle panel) or presence (right panel) of SN. Untreated tissue fixed upon arrival (left panel) was used as a negative control. Scale bars: 500 μm. (B) Tissues, *Salmonella* or both were conditioned or not for 1 h with SN and then extensively washed before being brought in contact for 1 h. Tissues were then treated with gentamicin for a further hour to kill extramucosal *Salmonella*, lysed and plated to evaluate colony forming units (CFUs). Bars show total CFUs of internalised *Salmonella*. Error bars represent SEM of four experiments; ***p<0.001 (ANOVA)."
value for testing the action of anti-inflammatory agents on both healthy and diseased tissues.

In this report we show that incubation of whole tissue with bacteria can lead to unreliable results as the bacteria can penetrate the tissue via a non-physiological route (e.g., from its broken edges) even if they are not invasive and enter into direct contact with components of the LP. We therefore generated a polarised organ culture system that also preserves the barrier properties of the mucus layer and its own microbiota. We achieved this by gluing a cylinder onto the apical side of the tissue, physically isolating the area of stimulus application. This allows the targeting of only the area that is exposed to the intestinal lumen, thus mimicking the in vivo situation as closely as possible. This methodology was also successfully used to analyse more fragile tissues such as those isolated from patients with IBD. To our knowledge, this is the first demonstration of the possibility of culturing a tissue in a polarised fashion for up to at least 24 h in optimal conditions.

We compared the activity of probiotics on tissue from the same patient and from the same area of the intestine, thus allowing for comparison with the basal cytokine secretion level and highly reproducible results. Bacterial stimulation was carried out in a conventional incubator for best bacterial growth conditions; however, the presence of oxygen was not killing the bacteria. Increased oxygen pressure is found at the interface between the epithelium and the lumen, indicating that hyperoxygenation may represent a physiological requirement. We also mimicked Salmonella infection in terms of pathology of the tissue and immune cytokine response. We observed an evident translocation of lymphoid aggregates and ulceration of the epithelium, with extensive crypt necrosis, glandular destruction and superficial atrophy. With this system we demonstrated an anti-inflammatory effect of a probiotic SN on Salmonella-induced inflammation. We showed that, although Salmonella alone induced TNF production, its co-incubation with the postbiotic resulted in the abrogation of TNF release without affecting IL-10 production. This was dependent on a direct effect of the SN on the tissue and not on Salmonella, and was enhanced when the tissue was preconditioned. We showed that the SN also exerts its anti-inflammatory potential on IBD tissues. We also unexpectedly observed that not all probiotics are harmless even on healthy tissues, and some strains such as *L. plantarum* NCIMB8826 can induce a local inflammatory response that resembles the response induced by *Salmonella*. By contrast, all tested probiotic strains, including *L. paracasei*, which we earlier showed to be protective in a mouse model of experimental colitis, are detrimental on

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**Figure 7** *Lactobacillus paracasei* culture supernatant (SN) is capable of significantly downregulating basal secretion of proinflammatory cytokines and chemokines and greatly reduces nuclear factor-κB (NF-κB) activation on inflammatory bowel disease tissue. (A) Tissues were incubated with medium (C-) or 5% SN as described in the text. Cytokines were measured in the basolateral culture medium by cytometric bead array; *p*<0.05, **p*<0.01. (B) Immunohistochemistry for NF-κB (p65, brown) after incubation of a representative Crohn’s disease (CD) tissue sample with or without SN as described in the text. Healthy tissue was used as a negative control for nuclear p65. Scale bars: 100 μm. (C) Quantification of results shown in (B). 2.5mm² areas were counted on three different samples; **p*<0.01 (Wilcoxon test).
inflamed IBD tissues. This is probably due to the increased intestinal permeability in IBD tissues, which could lead to increased bacterial translocation through the epithelial monolayer and activation of underlying infiltrating cells.

Together, our data indicate that probiotics would be more adequately used in patients in remission and not during the acute phase of the disease. However, this cannot be generalised to all strains and case-by-case preclinical studies on valid models are required before entering the clinics. The use of a probiotic like the one described here could be an effective and safe alternative for the treatment of acute IBD.

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Competing interests None.

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Contributors MR supervised the work and wrote the manuscript; KT developed the model, performed the experiments and wrote the manuscript; TB helped to develop the model; GP helped with data interpretation and manuscript editing; FC provided IBD model, performed the experiments and wrote the manuscript; OA provided anti-inflammatory compound.

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