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Administration of the Hyper-immune Bovine Colostrum Extract IMM-124E Ameliorates Experimental Murine Colitis

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Abstract

Background and Aims: Inflammatory bowel disease [IBD] is accompanied by lesions in the epithelial barrier, which allow translocation of bacterial products from the gut lumen to the host's circulation. IMM-124E is a colostrum-based product containing high levels of anti-E.coli-LPS IgG, and might limit exposure to bacterial endotoxins. Here, we investigated whether IMM-124E can ameliorate intestinal inflammation.

Methods: Acute colitis was induced in WT C57Bl/6J mice by administration of 2.5% dextran sodium sulphate [DSS] for 7 days. T cell transfer colitis was induced via transfer of 0.5×10^6 naïve T cells into RAG2$^{-/-}$ C57Bl/6J mice. IMM-124E was administered daily by oral gavage, either preventively or therapeutically.

Results: Treatment with IMM-124E significantly ameliorated colitis in acute DSS colitis and in T cell transfer colitis. Maximum anti-inflammatory effects were detected at an IMM-124E concentration of 100 mg/kg body weight, whereas 25 mg/kg and 500 mg/kg were less effective. Histology revealed reduced levels of infiltrating immune cells and less pronounced mucosal damage. Flow cytometry revealed reduced numbers of effector T helper cells in the intestine, whereas levels of regulatory T cells were enhanced. IMM-124E treatment reduced the DSS-induced increase of serum levels of lipopolysaccharide [LPS]-binding protein, indicating reduced systemic LPS exposure.

Conclusions: Our results demonstrate that oral treatment with IMM-124E significantly reduces intestinal inflammation, via decreasing the accumulation of pathogenic T cells and concomitantly increasing the induction of regulatory T cells. Our study confirms the therapeutic efficacy of IMM-124E in acute colitis and suggests that administration of IMM-124E might represent a novel therapeutic strategy to induce or maintain remission in chronic colitis.

Key Words: Systemic LPS exposure; novel therapeutic approach in IBD

1. Introduction

Inflammatory bowel disease [IBD], with its two main sub-forms ulcerative colitis [UC] and Crohn's disease [CD], is an important health problem with worldwide increasing prevalence.[1,2] IBD is characterised by chronic and relapsing intestinal inflammation, and affected patients suffer from significant clinical symptoms such as abdominal pain, diarrhoea, or fever.[3] Extra-intestinal manifestations such as inflammation of the skin, joints, liver, or eyes are common complications.[4,5] Though the exact pathophysiology is still unknown, it is evident that genetic factors, environmental triggers, and aberrant immune responses towards the commensal microbiota contribute to the development of IBD.[2,5–7]

The human intestine is populated by up to 10^{13} microbes, which form a complex ecosystem.[8,9] These microbes are usually harmless or even beneficial to the host,[10] but some microbial products, including the bacterial cell wall component lipopolysaccharide [LPS], can promote immune responses and thereby contribute to the development, progression, and exacerbation of IBD.[11] To prevent translocation of pro-inflammatory products from the gut lumen into the systemic circulation, where they elicit strong immune reactions, an adequate protective immunity towards invading bacteria is crucial. This includes a tight epithelial barrier, as well as rapid clearance of bacterial products and invading pathogens by innate immune cells located directly beneath the epithelial layer.[9,12] In addition, the production of immunoglobulins [Ig] against bacterial products prevents those molecules passing the epithelial surface.[13,14] Further, IgA seems to be involved in determining the composition of the intestinal microbiome,[13,14] which is also a crucial factor for intestinal health.[8] In IBD these first-line defence mechanisms are disturbed, and increased levels of bacterial products, including LPS, are detected in the serum.[15–17] LPS triggers the activation of toll-like receptor [TLR]4 on host cells, resulting in production of IL-6, tumour necrosis factor [TNF], interferon [IFN]-γ, and nitric oxide, which contributes to pro-inflammatory reactions and exacerbation of the disease.[15]

Colostrum is the milk produced by lactating mammals within the first 72 h after giving birth. In comparison with normal milk, colostrum contains high levels of immune-active molecules, such as IgA/IgG, growth factors, and anti-microbial agents [e.g. lysozyme and lactoperoxidase], as well as lactoferrin and vitamins.[18–20] In contrast to human colostrum which is rich in IgA, the main immunoglobulin found in bovine colostrum is IgG. This is of interest, since IgA can pass mucosal surfaces via the IgA transporter and possibly translocate to the systemic circulation, whereas IgG remains in the intestinal lumen. IMM-124E is a bovine colostrum-based product obtained from cows that have been immunised with LPS from *Escherichia coli*, which results in high levels of LPS-specific IgG. A study investigating the composition of IMM-124E has been published recently, showing that 1 mg IMM-124E powder contains about 0.4 mg total IgG, which is comparable to the total IgG content in colostrum powder.[21] In previous studies, it has been demonstrated that administration of IMM-124E ameliorates disease in a model of non-alcoholic steatohepatitis [NASH],[22,23] a disease where chronic presence of LPS and subsequent low-grade inflammation might promote disease activity.[24,25] Further, in TNBS-induced colitis, IMM-124E treatment resulted in reduced colitis severity and promoted the development of CD4+CD25+ regulatory T cells,[26] but its effect on barrier disruption-mediated colitis has not been addressed so far. In addition, IMM-124E treatment fostered the development of CD25high regulatory T helper and regulatory NKT cells in a mouse model of NASH,[22] indicating that IMM-124E might have potent immune cell modulatory effects.

Here, we further investigated the anti-inflammatory potential of IMM-124E in two mouse models of colitis, namely the dextran sodium sulphate [DSS] model of acute barrier disruption-induced colitis and the naïve T cell transfer model of colitis, to provide the rationale for its use in IBD patients.

2. Methods

2.1. Mice, colitis induction, weight recording, and IMM-124E treatment

All animal experiments were conducted according to Swiss animal welfare legislation and were approved by the local animal welfare office [Cantonal veterinary office Zurich; licence number ZH121/2017]. Female C57Bl/6J mice in a weight range between 21 and 23 g were obtained from Janvier Elevages [France] and maintained in a specific pathogen-free [SPF] environment with water and food *ad libitum*. To induce acute DSS colitis, mice were randomised into groups with equal average weight and were administered 2.5% dextran sodium sulphate [DSS, MW 36'000-50-000] in the drinking water for 7 days. RAG2-/- mice on a C57Bl/6J background were initially obtained from Taconic [Rensselaer, NY], and a local colony maintained in our SPF facility. To induce T cell transfer colitis, CD4+CD62LhighCD44low naïve T cells were sorted from the spleen of C57Bl/6J donor mice and 0.5 x 10^6 T cells were injected per RAG2-/- recipient. After 4 weeks, mouse endoscopy was performed as described below, and mice were randomised into groups with equal colitis severity before start of treatment. Weight of the mice was recorded daily at the same time. On the last day of the experiment, colonoscopy [see below] was performed in all animals. Directly after colonoscopy, blood was collected to obtain serum and mice were sacrificed via cervical dislocation before tissue collection for downstream applications. IMM-124E and colostrum control powder were provided by Immuron Ltd [Melbourne, Australia] and freshly emulsified at an appropriate concentration in autoclaved water directly before administration via oral gavage. The following treatment groups were used in DSS colitis: preventive treatment: 100 mg/kg body weight or 500 mg/kg IMM-124E per day, starting 2 days before beginning of DSS application [Day 2 of the experiment]. Administration of 100 mg/kg colostrum from non-immunised cows served as a treatment control. Therapeutic treatment onsisted of 500 mg/kg IMM-124E per day, starting at Day 3 of the DSS treatment. In transfer colitis, the following treatment groups were studied: 25 mg/kg, 100 mg/kg, or 500 mg/kg IMM-124E once per day. Administration of 100 mg/kg bovine serum albumin [BSA] or transfer of regulatory T cells served as controls.

2.2. Mouse endoscopy

To assess macroscopic colitis severity, mice were anaesthetised with 100 mg/kg body weight ketamine [Vétoquinol, Bern, Switzerland] and 8 mg/kg body weight Xylazine [Bayer, Lyssach, Switzerland] intraperitoneally [i.p.].. Animals were examined as described previously[27]: recording was performed with the Karl Storz Tele Pack Pal 20043020 [Karl Storz Endoskope, Tuttlingen, Germany], and colitis severity scored using the murine endoscopic index of colitis severity [MEICS] scoring system as described previously[28] using the following five parameters: [1] transparency of the colon, [2] changes of the vascular pattern, [3] fibrin visibility, [4] granularity of the mucosal surface, and [5] stool consistency.

2.3. Colon length measurement

The entire colon was resected from each mouse, and the length from the caecum to the anus measured before dissection to obtain tissue pieces for downstream applications such as histology, RNA/protein isolation, and myeloperoxidase [MPO] assay.

2.4. Histology

For histological assessment of colitis severity, mice were sacrificed and 1.5-cm long pieces from the terminal colon collected and transferred into 4% formalin solution. After 24 h, pieces were dehydrated in ascending alcohol series and Histoclear® [Chemie Brunschwig, Basel, Switzerland] before embedding in paraffin. The samples were cut into 4-μm thin sections, transferred onto glass cover slides, and air-dried. Sections were then rehydrated [incubation in Histoclear®, followed by descending ethanol series], incubated for 10 min in Hemalaun solution [Chemie Brunschwig], rinsed for 10 min in water, incubated for 15 s in Eosin solution [2% w/v; Sigma-Aldrich, Buchs, Switzerland], briefly rinsed in water, dehydrated in ascending alcohol series and Histoclear, and finally mounted with Histopaque embedding solution [Chemie Brunschwig]. The extent of colitis was assessed using the following parameters as described previously[29]: epithelial damage [0 = normal appearance, 1 = partial loss of goblet cells, 2 = extended loss of goblet cell, 3 = loss of crypt in small areas, 4 = extended loss of crypts] and infiltration/inflammation [0 = no infiltration or thickening, 1 = infiltration around the crypt area, 2 = infiltration of the mucosa, 3 = infiltration of the submucosa, mild oedema, 4 = infiltration reaches the muscularis submucosae, pronounced oedema].

2.5. Myeloperoxidase activity assay

Colon specimens were homogenised in 50 mM phosphate buffer [pH 6.0] and 0.5% hexadecyltrimethylammonium bromide [Sigma-Aldrich] using a GentleMACS tissue homogeniser [Miltenyi Biotech, Bergisch Gladbach, Germany]. After three freeze and thaw cycles, supernatant was mixed with 0.02% dianisidine [Sigma-Aldrich] in 50 mM phosphate buffer, pH 6.0, and 0.0005% H_2O_2 [Sigma-Aldrich]. Myeloperoxidase activity, expressed as arbitrary units, was calculated as mean absorbance [460 nm] per incubation time [in min] per protein content [in g].

2.6. RNA extraction and real-time polymerase chain reaction

Colon tissue was mechanically dissociated and lysed in RLT buffer [Qiagen, Venlo, The Netherlands] using a GentleMACS tissue homogeniser [Miltenyi Biotec]. Total RNA was isolated from the lysates using RNeasy Mini Kit [Qiagen], and DNA removed by TURBO DNA-free Kit [Ambion, Austin, TX] according to manufacturer's instructions. RNA concentration was assessed by absorbance at 260 and 280 nm. Complementary DNA [cDNA] synthesis was performed using a High-Capacity cDNA Reverse Transcription Kit [Applied Biosystems, Foster City, CA] following the manufacturer's instructions. Real-time polymerase chain reaction [RT-PCR] was performed using FAST qPCR MasterMix for Taqman Assays [Applied Biosystems] on a Fast HT7900 Real-Time PCR system using SDS Software [Applied Biosystems], or on a QuantStudio 6 System from Thermo Fisher Scientific [Waltham, MA]. Measurements were performed in triplicate, mouse GAPDH was used as endogenous control, and results were analysed by the ΔΔCT method. The real-time PCR contained an initial enzyme activation step [5 min, 95°C] followed by 45 cycles consisting of a denaturing [95°C, 15 s] and an annealing/extending [60°C, 1 min] step. The used gene expression assays were all obtained from Thermo Fisher Scientific.

2.7. Protein extraction and western blot

Colon pieces were disrupted in M-PER buffer [Thermo Fisher Scientific] using a GentleMACS tissue homogeniser. Equal amounts of proteins were loaded on polyacrylamide gels and, after separation by gel-electrophoresis, were blotted onto nitrocellulose membranes. Membranes were blocked in a 1% BSA and 3% milk-containing blocking solution, and incubated overnight in blocking solution with an appropriate concentration of primary antibody. Membranes were washed three times with washing buffer (Tris buffered saline containing 1% Tween 20 [1% TBST]) before incubation with HRP-coupled anti-rabbit secondary antibody [Lab Force, Santa Cruz, CA] for 2 h. Immunoreactive proteins were detected with a Fusion Solo S imager [Vilber Lourmat, Witec AG, Littau, Switzerland] using a western blotting detection kit [Western Bright Sirius or ECL, Advansta, Menlo Park, CA]. Anti-phospho NF-κB-p65 [Ser536] and anti-NF-κB-p65, antibodies were obtained from Cell Signaling Technologies [Danvers, MA].

2.8. IgG depletion from IMM-124E

To deplete IgG from IMM-124E, the IMM-124E suspension was incubated with Sepharose A beads [250 μl beads/ml suspension] for 2 h at room temperature. As control, IMM-124E suspension was incubated with non-protein coupled Sepharose beads for 2 h. The suspensions were then centrifuged at 250 x g for 2 min, and supernatants used for gavages.

2.9. Colon explants

For colon explants, 1 cm of the colon was opened longitudinally, rinsed with PBS and cultured for 24 h in 0.5 ml RPMI [Thermo Fisher Scientific] supplemented with 10% FCS, and 1% penicillin/streptomycin solution [Thermo Fisher Scientific] in an incubator [37°C, 10% CO_2].

2.10. Enzyme-linked immunosorbent assay

Cytokine measurements were performed using commercial ELISA kits from R&D [Minneapolis, MN; IL-6, IL-10, TNF, IFN-γ] and HycultBiotech [Uden, The Netherlands; LBP ELISA]. All assays were performed according to the manufacturer's instructions.

2.11. Flow cytometry

Lamina propria immune cells were isolated as described previously.[27,30] In brief, the colon was opened, rinsed in PBS, and cut in 0.5-cm pieces, and epithelial cells were removed by repeated incubation in EDTA-containing HBSS and rigorous shaking. Tissue pieces were then digested for 15–25 min. in RPMI supplemented with 10% FCS, 0.6 mg/ml collagenase IV [Roche, Basel, Switzerland], and 2.4 mg/ml dispase [Sigma-Aldrich]. Remaining tissue was homogenised using a 26 G needle and passed over a 40 μm mesh. For intracellular cytokine staining, cells were treated with PMA [50 ng/ml, Sigma-Aldrich, Buchs, Switzerland], ionomycin [1 μg/ml, Sigma-Aldrich] in the presence of 10 ng/ml Brefeldin A [Sigma-Aldrich] for 3 h. Cells were harvested, washed in PBS, stained for surface molecules for 30 min, washed in FACS buffer [PBS, 2% FCS], and fixed in fixation/permeabilisation buffer [BD, Franklin Lakes, NJ] for 15 min. Cells were washed and resuspended in permeabilisation buffer [BD] before addition of anti-IFN-γ and anti-IL-17 antibody for 15 min. Before analysis, cells were washed in permeabilisation

buffer and re-suspended in FACS buffer. An LSR Fortessa analyser from BD was used for all analysis.

2.12. LPS measurement in mouse serum

HEKblue-mTLR4 cells [Invivogen] were cultured in DMEM [Thermo Fisher Scientific] supplemented with 10% FCS and 2 mM L-glutamine. For LPS detection, 20 μl serum was added to 96-well plates, and 200'000 HEKblue-mTLR4 cells in 180 μl HEK-Blue detection medium [Invivogen] were added per well. After 24 h, absorbance at 630 nm was measured and concentrations calculated based on a standard curve prepared from pure LPS diluted in mouse serum.

2.13. Statistics

Unless otherwise stated, data are presented as means ± standard error of the mean [SEM] for one out of two independent experiments; n equals the number of mice in one experiment. Statistical analysis was performed by analysis of variance [ANOVA] followed by Mann-Whitney U testing, and Bonferroni correction was used to correct for multiple testing; P-values <0.05 were considered significant.

3. Results

3.1. Administration of IMM-124E prevents acute DSS-induced colitis

To test whether administration of IMM-124E is able to ameliorate colitis *in vivo*, we induced acute colitis in WT C57Bl/6J mice via administration of 2.5% DSS in the drinking water for 7 days. This treatment resulted in severe intestinal inflammation, characterised by diarrhoea, severe weight loss [Figure 1A], macroscopic signs of colitis on endoscopy accompanied by elevated MEICS score [colon wall thickening, disturbed vascularisation pattern, granular appearance of the colon wall, fibrin deposits, and loose stool, Figure 1B, C], shortening of the colon [Figure 1D], increased levels of myeloperoxidase in colon tissue [Figure 1E], and histological signs of severe colitis [erosion of the epithelium, infiltration of immune cells, oedema in the subepithelium; Figure 1F–I].

To test whether IMM-124E prevents colitis development, mice were treated with 100 mg/kg body weight or 500 mg/kg IMM-124E per day, starting 2 days before beginning of DSS application [preventive treatment]. Administration of 100 mg/kg colostrum from non-immunised cows served as a treatment control. Another group received 500 mg/kg IMM-124E in a therapeutic setting, starting the gavages at Day 3 of the DSS treatment. Of interest, all treatment schedules resulted in less severe weight loss in comparison with DSS only [Figure 1A], and colon length was not changed in any of the treatment groups [Figure 1D]. However, other indicators of colitis severity showed clear differences between the treatment groups: for instance, MPO levels were only reduced in mice treated with 100 mg/kg IMM-124E, whereas 500 mg/kg IMM-124E [preventive or therapeutic] and colostrum administration did not affect MPO activity [Figure 1E]. Preventive treatment with IMM-124E [100 mg/ kg and 500 mg/kg] or with colostrum resulted in less severe colitis, as observed in mouse endoscopy, although therapeutic treatment did not significantly reduce macroscopic signs of colitis [Figure 1B, C]. Preventive 100 mg/kg IMM-124E treatment had the most pronounced effect, which was most overt in reduced levels of disturbed vascularisation and granularity of the colon wall. Histological assessment of the terminal colon revealed that preventive treatment with 100 mg/kg IMM-124E significantly reduced epithelial damage

and, albeit not statistically significant [$p = 0.06$], infiltration of immune cells into the submucosal layer, resulting in a reduction of total histology score [Figure 1F–I]. Of note, none of the other treatments did result in a significant reduction of histological parameters of colitis. This clearly indicates that IMM-124E treatment prevents DSS-induced colitis, and that treatment with 100 mg/kg IMM-124E is most effective.

3.2. IMM-124E reduces pro-inflammatory cytokine production

To understand the molecular mechanisms by which IMM-124E reduced the extent of colitis in the acute DSS model, we next studied mRNA expression of pro- and anti-inflammatory cytokines in colon tissue from DSS-treated mice that received IMM-124E either preventively [100 mg/kg and 500 mg/kg] or therapeutically [500 mg/ kg]. Of note, DSS treatment resulted in enhanced expression of *Il6*, *Il10*, *Ifng*, and *Tnfa*. Although preventive IMM-124E and colostrum administration inhibited the increase in *Il6* and *Il10* mRNA expression [Figures 2A+B], elevated *Ifng* and *Tnfa* expression was still present [Figure 2C+D]. In line with increased mRNA expression upon DSS administration, IL-6, IFN-γ, and TNF cytokine levels in the supernatant of colon explants from DSS-treated mice were also elevated [Figure 2E–H]. Of interest, cytokine levels of IL-6, IFN-γ, and TNF were significantly reduced in the supernatant of colon explants from mice that received 100 mg/kg IMM-124E, whereas preventive treatment with 500 mg/kg IMM-124E resulted in decreased IL-6 and IFN-γ levels only, and treatment with 100 mg/kg colostrum had no effect on the secretion of these cytokines [Figure 2E, G, H]. IL-10 levels were not significantly affected by any of the treatments [Figure 2F].

3.3. IMM-124E ameliorates T cell-mediated colitis

DSS treatment results in erosion of the epithelial layer, and thus represents important features that contribute to colitis onset in IBD patients. However, it only partially reflects the involvement of immune cells in the pathogenesis of intestinal inflammation. In particular, the effect of pathogenic T cell responses is not reflected in this model.[31] Therefore, we next investigated the effect of IMM-124E treatment in the T cell transfer model of colitis, where naïve T cells are transferred into B and T cell deficient recipients. As expected, T cell transfer resulted in first signs of colitis after 3 weeks, characterised by onset of diarrhoea and macroscopic signs of colon inflammation on mouse endoscopy [Figure 3A]. Upon onset of colitis, mice were randomised into groups with equal colitis severity and were treated with 25 mg/kg, 100 mg/kg, or 500 mg/kg IMM-124E once per day. Since colostrum itself contains high levels of IgG and other factors that might act as confounders, administration of 100 mg/kg BSA or transfer of regulatory T cells served as controls. Although weight development did not differ significantly between the treatment groups [not shown], colonoscopy revealed that colitis was clearly reduced in mice receiving 100 mg/kg IMM-124E 2 weeks after the start of IMM-124E treatment [Figure 3B], an observation that was confirmed by assessment of spleen weight, colon length, and histology scores [Figure 3C-F].

3.4. IMM-124E affects immune cells in the inflamed colon

It has previously been shown that IMM-124E treatment results in enhanced levels of CD4+CD25+ regulatory T cells in a TNBS-mediated colitis model as well as in NASH patients.[22,23] To address
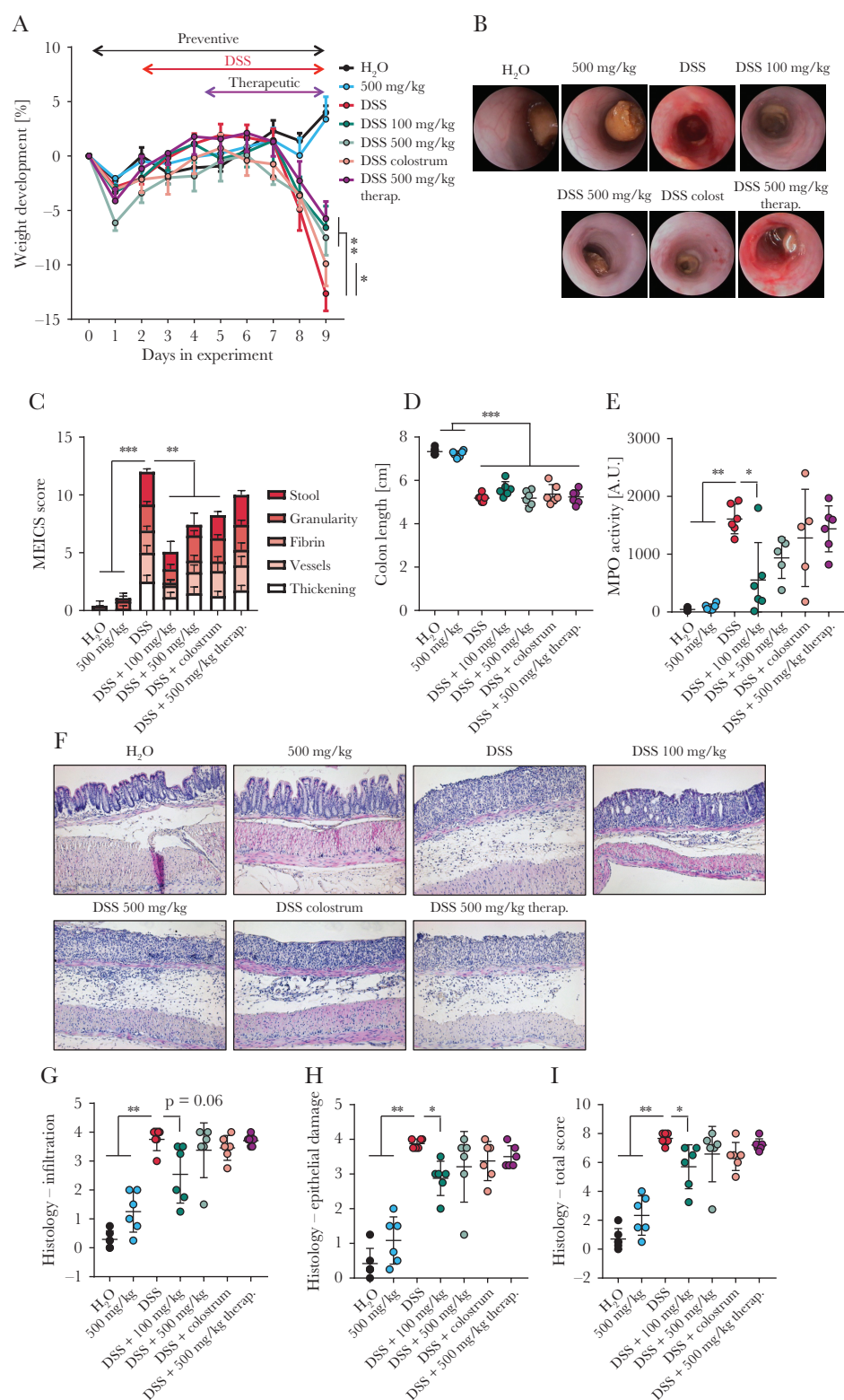
Figure 1. IMM-124E administration prevents acute DSS colitis. Acute colitis was induced in female C57Bl/6J mice via administration of 2.5% DSS in the drinking water for 7 days [Days 2–9 of the experiment]. Mice received 100 mg/kg or 500 mg/kg body weight IMM-124E per daily oral gavage starting at Day 0 [preventive treatment] or at Day 4 [therapeutic treatment]. Depicted are: A] weight development, B] representative pictures from mouse endoscopy, C] respective scoring according to the of murine endoscopy index of colitis severity [MEICS] score, D] colon length, E] myeloperoxidase [MPO] activity in the colon, E] representative pictures of H&E-stained terminal colon sections, and scoring of F] epithelial damage, G] inflammation, and H] summarised histological score. Asterisks denote significant differences [* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$]. A + C: $n = 6$ per group. Data are represented as mean ± SEM. D–H: each dot represents one individual mouse, horizontal bars stand for mean, whiskers indicate SEM. DSS, dextran sodium sulphate; H&E, haematoxylin and eosin; SEM, standard error of the mean.
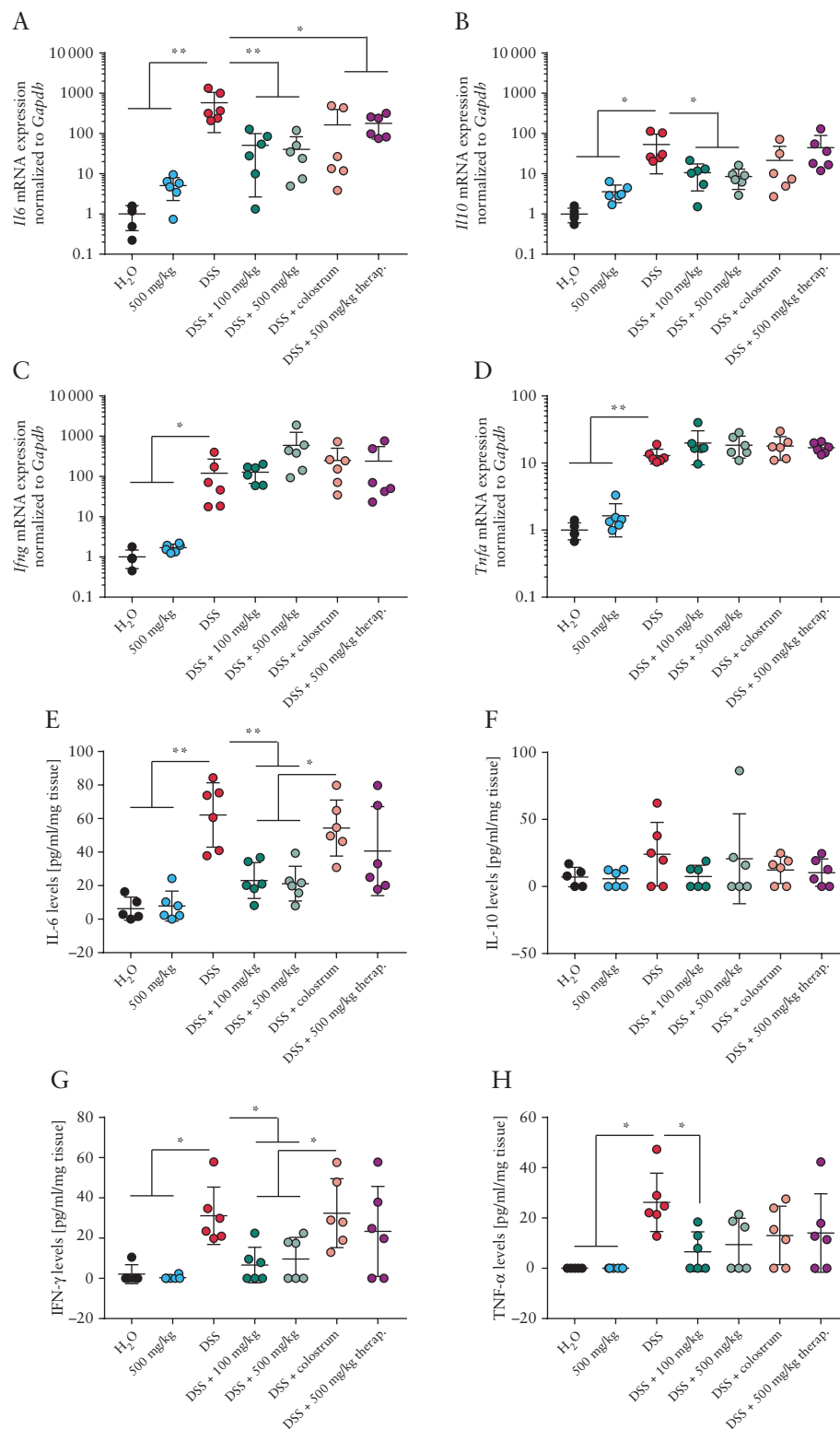
Figure 2. IMM-124E prevents DSS-induced elevation of IL-6, IFN-γ and TNF-α. Acute colitis was induced in female C57Bl/6J mice via administration of 2.5% DSS in the drinking water for 7 days [Days 3–9 of the experiment]. Mice received 100 mg/kg or 500 mg/kg body weight IMM-124E per daily oral gavage starting at Day 1 [preventive treatment] or at Day 5 [therapeutic treatment]. A–D: mRNA expression levels of the indicated genes in the terminal colon were analysed by RT-PCR and normalised to *Gapdh* and the median of untreated controls. E–H: Colon pieces were incubated in RPMI for 24 h and levels of the indicated cytokines in the supernatant analysed by ELISA. Each dot represents an individual mouse, horizontal bars indicate mean, and whiskers indicate SEM. Asterisks denote significant differences [* = $p < 0.05$; ** = $p < 0.01$]. DSS, dextran sodium sulphate; SEM, standard error of the mean; RT-PCR, real-time polymerase chain reaction.
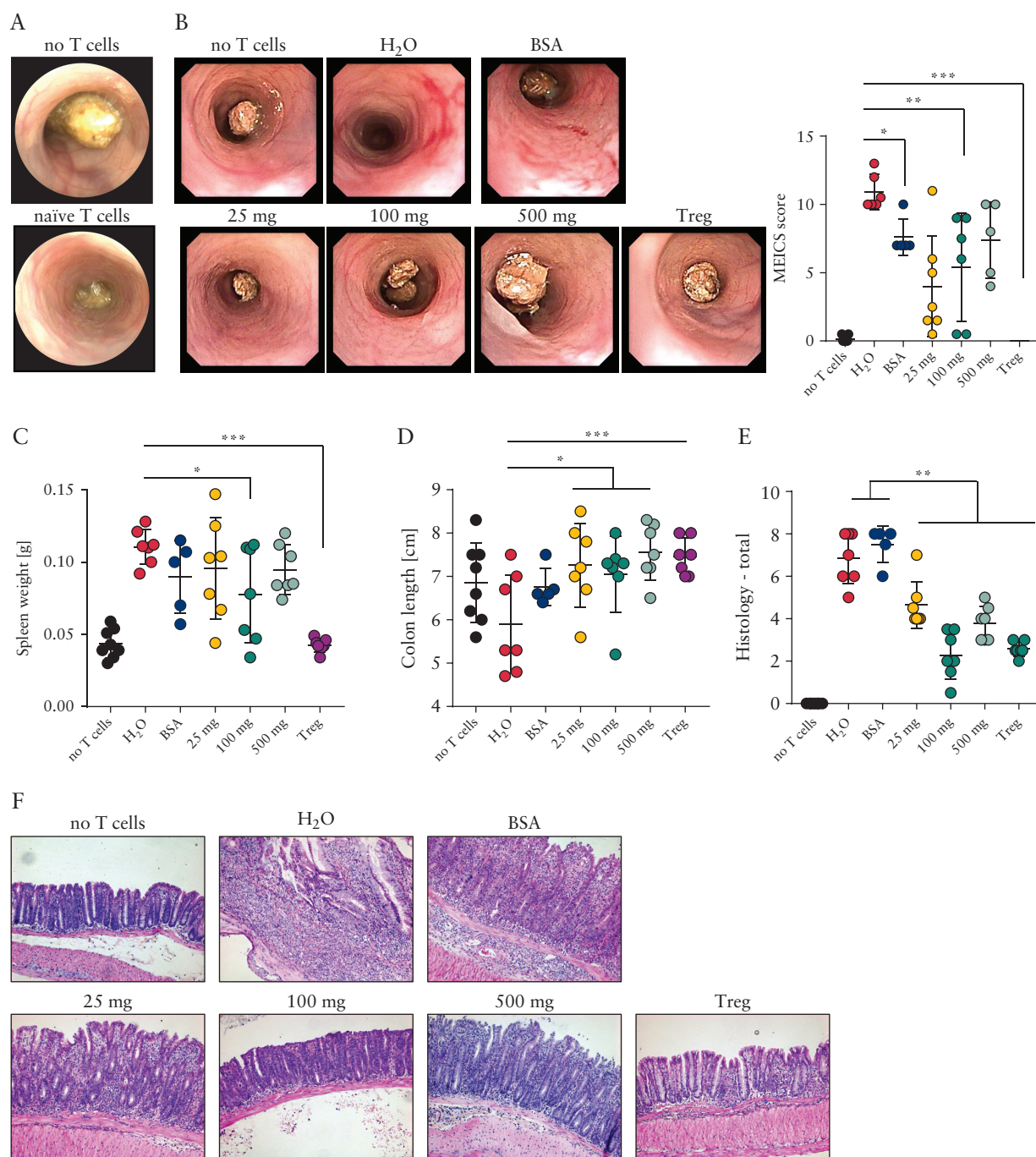
Figure 3. IMM-124E ameliorates T cell transfer colitis. Colitis was induced in RAG2$^{-/-}$ mice via transfer of 0.5 x 10^6 naïve T cells. Control mice received no T cells or 0.5 x 10^6 naïve T cells + 0.5 × 10^6 regulatory T cells. At Day 24, colonoscopy was performed to verify colitis induction, and mice were distributed into groups with equal colitis severity. Starting at Day 24, mice received 25 mg/kg, 100 mg/kg, or 500 mg/kg IMM-124E, or 100 mg/kg BSA, per daily oral gavage until the end of the experiment 4 weeks later. Depicted are: A] representative pictures from colonoscopy on Day 24, B] representative pictures and scoring according to the murine endoscopic index of colitis severity [MEICS] score from colonoscopy at the end of the experiment, C] spleen weight, D] colon length, E] histological scoring, and F] representative pictures of H&E stained sections of the terminal colon. Each dot represents an individual mouse, horizontal bars indicate mean, and whiskers indicate SEM; n = 7 for each group, except control without T cells [n = 8] and BSA [n = 5]. Asterisks denote significant differences [* = p < 0.05; ** = p < 0.01]. H&E, haematoxylin and eosin; SEM, standard error of the mean.

whether IMM-124E treatment also affects CD4+ T cells in the transfer colitis model, we performed flow cytometry on mesenteric lymph nodes [mLN] and colonic lamina propria lymphocytes [LPL]. Flow cytometry revealed that administration of IMM-124E resulted in reduced levels of Th effector cells in mLN and LPL. In particular,

proportions of CD4$^+$ IFN-γ $^+$ Th1, IL-17$^+$ Th17, and IL-13$^+$ Th2 cells were reduced [Figure 4A-C], whereas the proportion of FoxP3$^+$ regulatory T cells was enhanced in the colonic lamina propria and mLN of mice treated with 100 mg/kg IMM-124E [Figure 4D]. Although 25 mg/kg and 500 mg/kg IMM-124E treatment had some effect on
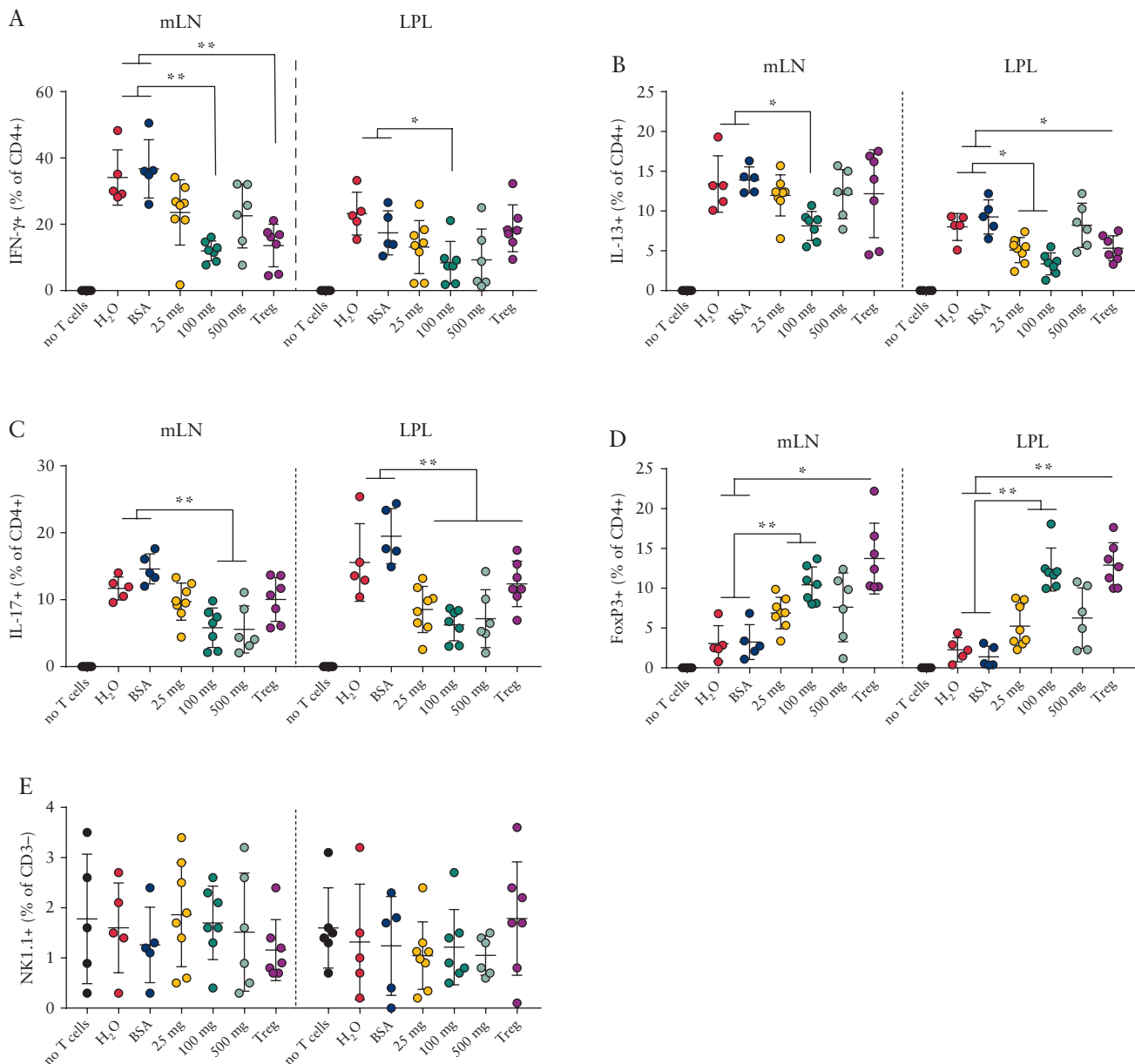
Figure 4. Altered immune cell subsets upon treatment with IMM-124E. Colitis was induced in RA G2$^{-/-}$ mice via transfer of 0.5 x 10^6 naïve T cells. Control mice received no T cells or 0.5 x10^6 naïve T cells + 0.5 × 10^6 regulatory T cells. At Day 24, colonoscopy was performed to verify colitis induction, and mice were distributed into groups with equal colitis severity. Starting at Day 24, mice received 25 mg/kg, 100 mg/kg, or 500 mg/kg IMM-124E, or 100 mg/kg BSA, per daily oral gavage until the end of the experiment 4 weeks later. Immune cells from the mesenteric lymph nodes [mLN] or the lamina propria [LPL] were analysed by flow cytometry for: A–D]T cells expressing the indicated cytokines, and E] proportion of NK cells. Each dot represents an individual mouse, horizontal bars indicate mean, and whiskers indicate SEM. Asterisks denote significant differences [* = *p* < 0.05; ** = *p* < 0.01]. SEM, standard error of the mean.

Th cell subsets, this was clearly less pronounced. On the other hand, numbers of NK1.1$^+$ NK cells were very low and no significant effects were observed upon colitis induction or IMM-124E treatment [Figure 4E]. Of note, all the beneficial effects observed upon IMM-124E treatment were absent in the control group receiving BSA.

3.5. IMM-124E prevents systemic LPS exposure upon colitis induction

IMM-124E contains high levels of anti-LPS IgG, and might therefore neutralie LPS translocation from the gut lumen into the systemic circulation. Although LPS itself is typically below detection

limits, systemic exposure to LPS results in expression of LPS-binding protein [LBP], and LBP levels correlate with the extent of LPS exposure. Therefore, we next addressed whether LBP levels are increased in DSS colitis, and whether IMM-124E administration might affect LBP levels in the serum of DSS-treated mice. In line with a severe barrier defect, DSS treatment resulted in significantly enhanced serum levels of LBP [Figure 5A]. IMM-124E administration significantly reduced serum levels of LBP. However, and in contrast to a better response to 100 mg/kg IMM-124E with respect to colitis indicators, this effect was not dose-dependent, i.e. 500 mg/kg IMM-124E administration was as effective as 100 mg/kg, whereas
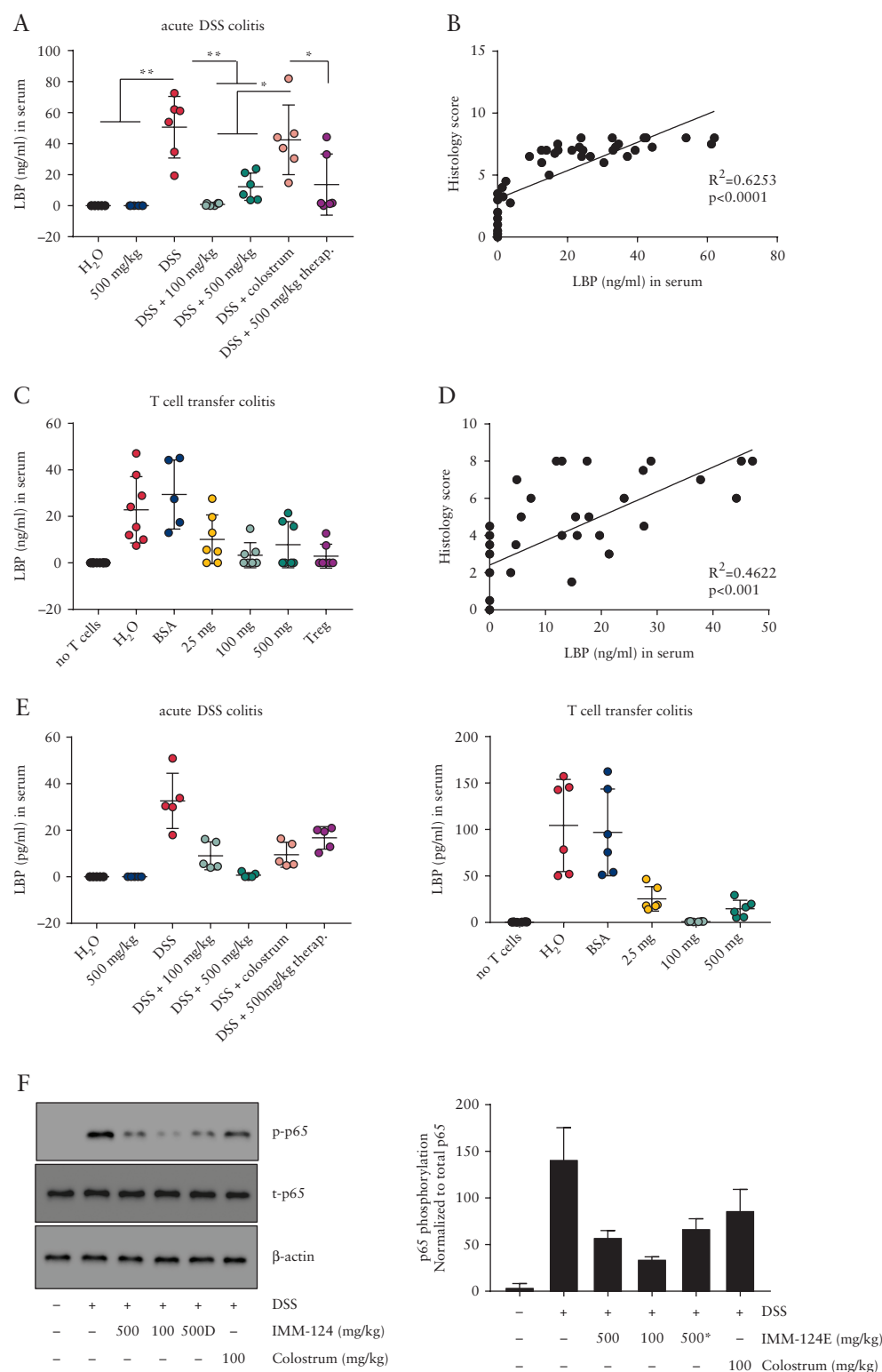
Figure 5. IMM-124E prevents systemic exposure to LPS. A+B] Acute colitis was induced in female B57BL/6 mice via administration of 2.5% DSS in the drinking water for 7 days [Days 3–9 of the experiment]. Mice received 100 mg/kg or 500 mg/kg body weight IMM-124E per daily oral gavage, starting at Day 1 [preventive treatment] or at Day 5 [therapeutic treatment]. Serum was collected at the end of the experiment and analysed for the concentration of LPS-binding protein [LBP] by ELISA [A], and LBP levels were correlated to total histology scores from the same mice [B]; $n = 6$ per group. C+D] Colitis was induced in RAG2$^{-/-}$ mice via transfer of 0.5×10^6 naïve T cells. Control mice received no T cells or 0.5×10^6 naïve T cells + 0.5×10^6 regulatory T cells. At Day 24, colonoscopy was performed to verify colitis induction, and mice were distributed into groups with equal colitis severity. Starting at Day 24, mice received 25 mg/kg, 100 mg/kg, or 500 mg/kg IMM-124E, or 100 mg/kg BSA per daily oral gavage until the end of the experiment 4 weeks later. Serum was collected at the end of the experiment and analysed for the concentration of LPS-binding protein [LBP] by ELISA [C] and LBP values correlated with total histology scores from the same mice [D]; $n = 7$ in each group, except no T cells control [$n = 8$] or BSA treated [$n = 5$] group. E] Serum from mice in A [acute DSS colitis] and C [T cells transfer colitis] was incubated

administration of colostrum did not affect serum LBP levels [Figure 5A]. Nevertheless, levels of LBP moderately correlated with histological scores [Figure 5B], indicating that systemic LPS translocation might be involved in mediating disease in DSS-induced colitis. LBP serum levels were also increased in T cell transfer colitis [Figure 5C], however to a lesser extent than in the DSS model. Again, IMM-124E administration reduced LBP levels in the serum, but there was only a weak correlation between LBP levels and total histology scores [Figure 5D]. To investigate whether there is direct presence of LPS in the mouse serum after colitis induction, we next used HEKble-mTLR4 cells. These cells carry a reporter for mouseTLR4 activation. When HEKble-mTLR4 cells were incubated with serum from control mice, there was no TLR4 activation detectable. DSS treatment in contrast resulted in TLR4 activation, indicating presence of LPS in those mice. In line with reduced LBP serum levels, TLR4 activation was lower in cells incubated with serum from IMM-124E-treated mice. Again, the 100 mg/kg IMM-124E was the most effective dose [Figure 5E]. To further investigate whether IMM-124E treatment reduces LPS-induced signalling cascades in DSS-treated mice, we analysed activation of NF-κB in colon lysates from mice with acute colitis with or without IMM-124E treatment. We saw a strong induction of NF-κB p65 phosphorylation in DSS-treated mice, which was clearly suppressed upon treatment with IMM-124E [Figure 5F]. To address whether IMM-124E treatment also results in reduced translocation of whole bacteria, we measured levels of bacterial 16S rDNA in mesenteric lymph nodes from our mice. However, we only observed 16S rDNA in very few mice, and did not observe any clear pattern [data not shown]. Taken together, these data indicate that IMM-124E-treatment prevents DSS-induced systemic exposure to LPS and LPS-induced pro-inflammatory signalling.

3.6. Therapeutic potential of IMM-124E is partially dependent on presence of IgG

To further investigate the mechanism of action of IMM-124E, we next performed an acute DSS colitis experiment using either the normal IMM-124E preparation, or IgG-depleted IMM-124E. In line with our findings that IMM-124E-treatment reduces exposure to LPS, which is likely due to high levels of anti-LPS antibody load, IgG depletion from IMM-124E partially abrogated the beneficial effect of IMM-124E [Figure 6].

4. Discussion

In this study, we demonstrated that administration of IMM-124E ameliorates colitis in two mechanistically different mouse models of intestinal inflammation, namely the DSS model of epithelial injury and the immune cell mediated T cell transfer colitis. IMM-124E administration significantly reduced DSS-mediated induction of pro-inflammatory cytokines in the intestine, including IL6 and TNF. In T cell transfer colitis, IMM-124E administration reduced levels of Th1, Th2, and Th17 cells, but promoted the induction of regulatory T cells. Further, IMM-124E significantly reduced systemic LPS exposure/presence of LPS in the serum.

Of interest, the most effective dose of IMM-124E administration was 100 mg/kg, which was even more effective than higher doses of

IMM-124. Since the exact mechanism by which Imm-124E works is still elusive, it is hard to tell why this might be the case. One possible explanation could be that high doses of IMM-124E might result in the formation of immune complexes of IgG with LPS, which could activate antigen-presenting cells in the intestine and thus promote pro-inflammatory effects. On the other hand, IMM-124E is a cow's milk-based product. Adult mice do not usually ingest milk and, in combination with a barrier defect, exposure to high levels of milk proteins might contribute to disease symptoms and thus suppress the beneficial effect of IMM-124E. However, further experiments would be required to understand the exact mechanism by which IMM-124E is most effective at 100 mg/kg.

A recent study that investigated how IMM-124E might exert its anti-diarrhoeagenic effects, demonstrated that IMM-124E has direct antibacterial activity via inhibition of growth and migration of bacteria.[21] This indicates that also during colitis, the beneficial effect of IMM-124E is possibly due to direct antibacterial properties, which might lead to decreased translocation of invading pathogens. However, we only observed 16S rDNA transcripts in mesenteric lymph nodes from very few DSS-treated mice. Additional experiments would be required to assess whether direct antimicrobial properties of IMM-124E play a role in protecting from colitis,.

It has previously been demonstrated that IMM-124E administration ameliorates insulin resistance and alleviates liver injury in a mouse model of NASH,[22] an effect associated with alteration in regulatory T cell and NKT cell proportions. In a small, open-label trial with 10 NASH patients, IMM-124E administration alleviated insulin resistance and improved lipid profile, which was accompanied by increased levels of regulatory T cells.[23] It has further been demonstrated that IMM-124E alleviates immune-mediated colitis in the TNBS model.[26] Also in this model, IMM-124E treatment resulted in elevated levels of regulatory T cells, and serum levels of IL-10 were significantly enhanced.[26] Whereas we also found significantly elevated levels of CD4+FoxP3+ regulatory T cells in the transfer colitis model, we did not see an effect on NK cells, possibly because the abundance of these cells is rather low in mLN and the lamina propria, and their abundance might be generally altered in RAG2-/- recipients due to absence of T. B, and NKT cells.

In colitis, altered cytokine responses significantly contribute to disease development and exacerbation.[32] IL-10 is one of the most important anti-inflammatory cytokines for the maintenance of intestinal health,[33–35] and defects in the IL-10 signalling pathway predisposes to very early onset of IBD.[36,37] Whereas Ya'acov *et al.* found increased levels of IL-10 in the serum of TNBS-treated mice that received IMM-124E,[26] we found that IMM-124E prevented DSS-induced induction of *IL10* mRNA expression, and there was no significant effect on IL-10 secretion. This indicates that in the DSS model, the effect of IMM-124E does not seem to be mediated via effects on the regulatory cytokine IL-10. In NASH patients treated with IMM-124E, an increase in IL-6 serum levels was observed.[23] However, in the DSS model, we observed an induction of IL-6 upon DSS treatment, which was reduced in IMM-124E treated mice. This might be due to different modes of action, i.e. the role of IL-6 in NASH remains controversial, with studies showing that blocking of IL-6 promotes disease[38] and activation of IL-6 signalling alleviated

with HEKblue-mTLR4 reporter cells for 48 h to determine presence of LPS. SEAP activity levels were measured at 620 nm and correspond to the amount of LPS present in the serum. F] Representative pictures and respective densitometric analysis of colon lysates from mice treated as in A [acute colitis]; *n* = 3 for each treatment condition. Each dot represents an individual mouse, horizontal bars indicate mean, and whiskers indicate SEM. Asterisks denote significant differences [* = *p* < 0.05; ** = *p* < 0.01]. In B + D, the line indicates the best fit. LPS, lipopolysaccharide; DSS, dextran sodium sulphate; SEM, standard error of the mean.
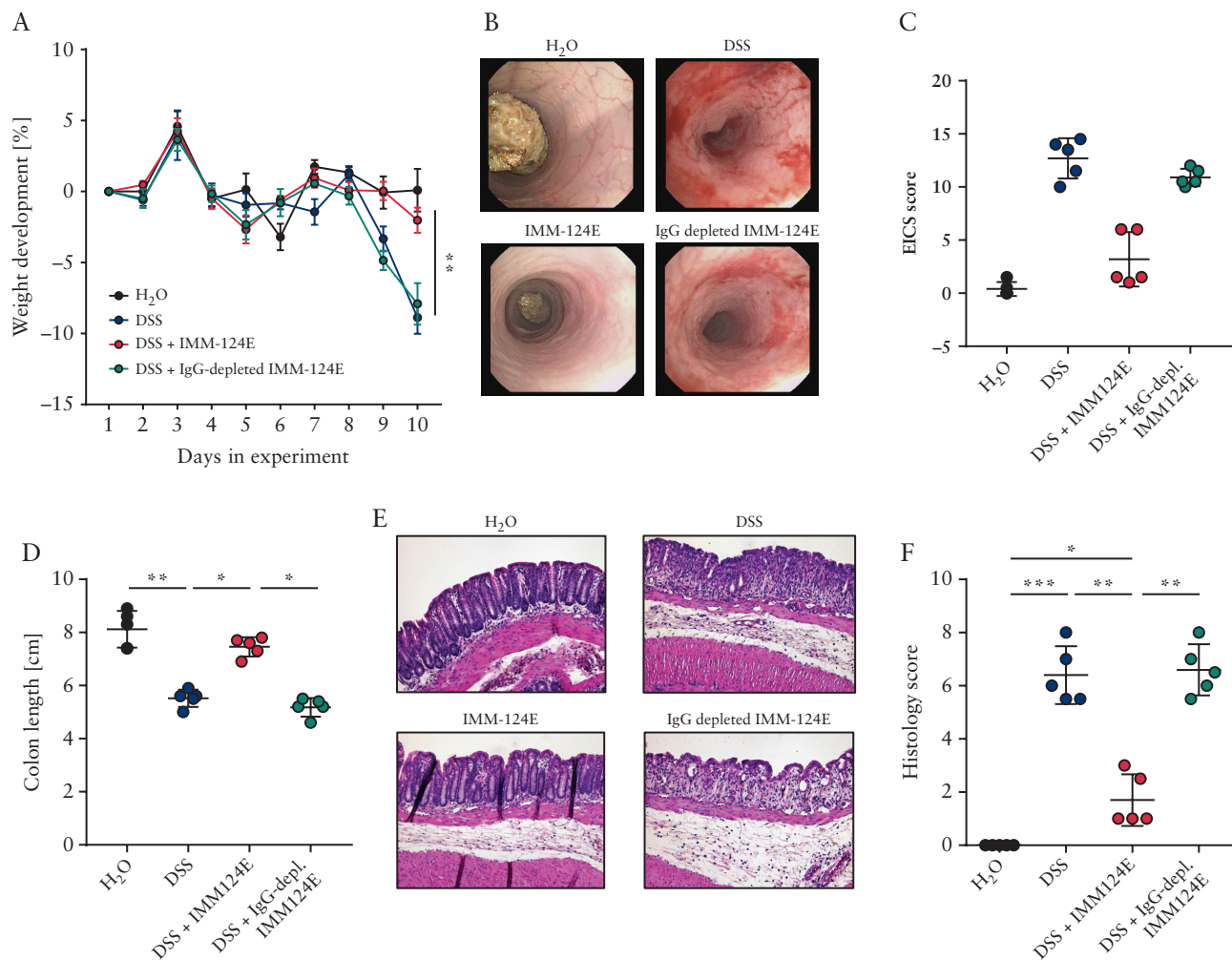
Figure 6. Depletion of IgG from IMM-124E partially abrogates its beneficial effect. Acute colitis was induced in female C57Bl/6J mice via administration of 2.5% DSS in the drinking water for 7 days [Das 2–9 of the experiment]. Mice received 100 mg/kg body weight normal IMM-124E, or IgG-depleted IMM-124E per daily oral gavage starting at Day 0. Depicted are: A] weight development, B] representative pictures from mouse endoscopy, C] respective scoring according to the of murine endoscopy index of colitis severity [MEICS] score, D] colon length, E] representative pictures of H&E-stained terminal colon sections, and F] histological scoring. Asterisks denote significant differences [* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$]; $n = 5$ per group. Data are represented as mean ± SEM, and each dot represents one individual mouse, horizontal bars stand for mean, whiskers indicate SEM. DSS, dextran sodium sulphate; H&E, haematoxylin and eosin; SEM, standard error of the mean.

disease in a NASH model,[39] whereas anti-IL6 treatment improved barrier function in DSS colitis[40] and ameliorated disease in a T cell transfer colitis.[41]

T helper cells play a major role in the development and progression of IBD,[42] and several studies demonstrated enhanced levels of IFN-γ+ Th1 and IL-17+ Th17 cells, whereas relative numbers of regulatory T cells were decreased [reviewed in[43]]. IMM-124E administration corrected the altered balance in Th cells in the transfer colitis models, via reduction of exacerbated Th cell responses and concomitant enhanced induction of regulatory T cells. This clearly demonstrates that IMM-124E administration reduces aberrant Th cell activation during colitis, and has the ability to promote anti-inflammatory responses.

NK cells and NKT cells are unique subsets of immune cells that produce large amounts of IFN-γ and TNF upon activation. Further, they exert cytotoxic functions and lyse aberrant cells, including tumour cells.[44] Adar *et al.* described increased levels of NK and NKT cells in IMM-124E treated ob/ob mice.[22] However, we could not

determine any difference in NK cell numbers in mesenteric lymph nodes or the lamina propria of IMM-124E-treated mice. Of note, NKT cells are absent in RAG2-/- mice, and cannot be studied in this model. The differences in NK cell induction between our study and the study from Adar *et al.* might further be explained by the fact that NK cells exert different effects depending on the disease context.[44] In experimental models of NASH, injection of NK cells alleviated disease via regulation of macrophage activation,[45,46] although studies of NK cell numbers in IBD have yielded conflicting results.[47,48]

Especially in the DSS colitis model, innate immune cells, including cells of the myeloid lineage such as macrophages and granulocytes, are important drivers of disease[31] and there is evidence that these cells also play crucial roles in the onset of IBD in humans.[49,50] We did not address immune cells in detail in the DSS model, but we measured MPO levels, which are a good indicator of myeloid cell infiltration and function.[51] In line with decreased levels of infiltrating immune cells in the inflamed colon of IMM-124E-treated mice, MPO levels were also significantly decreased, indicating that

in addition to preventing aberrant induction of Th cells, IMM-124E also prevents the accumulation of activated myeloid cells.

Summarised, our results demonstrate that IMM-124E administration significantly ameliorates experimental colitis and might be a promising novel therapeutic agent in IBD, either as a stand-alone treatment for maintaining remission in mild colitis cases or in combination with other treatments to increase therapeutic efficacy and prevent loss of therapeutic response.

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Conflict of Interest

None declared.

Author Contributions

MRS, KA, KB, HM: performed experiments; MRS, IFW: data analysis; DRP, GL, GR, MS: intellectual discussion and critical scientific input; MS, GR, IFW: study design; all authors wrote, corrected, and discussed the manuscript.

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