



**HAL**  
open science

## Divergent Roles for Macrophage C-type Lectin Receptors, Dectin-1 and Mannose Receptors, in the Intestinal Inflammatory Response

Mouna Rahabi, Godefroy Jacquemin, Mélissa Prat, Etienne Meunier, Mohamad Alaeddine, Bénédicte Bertrand, Khaddouj Benmoussa, Philippe Batigne, Agnès Aubouy, Johan Auwerx, et al.

► **To cite this version:**

Mouna Rahabi, Godefroy Jacquemin, Mélissa Prat, Etienne Meunier, Mohamad Alaeddine, et al.. Divergent Roles for Macrophage C-type Lectin Receptors, Dectin-1 and Mannose Receptors, in the Intestinal Inflammatory Response. *Cell Reports*, 2020, 30 (13), pp.4386-4398.e5. 10.1016/j.celrep.2020.03.018 . hal-02997537

**HAL Id: hal-02997537**

**<https://hal.science/hal-02997537v1>**

Submitted on 22 Aug 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial 4.0 International License

**Title: Divergent roles for macrophage C-type lectin receptors, Dectin-1 and Mannose Receptors, in the intestinal inflammatory response**

**Authors:** Mouna Rahabi<sup>1,8</sup>, Godefroy Jacquemin<sup>1,8</sup>, Mélissa Prat<sup>1</sup>, Etienne Meunier<sup>1</sup>, Mohamad AlaEddine<sup>1</sup>, Bénédicte Bertrand<sup>1</sup>, Lise Lefèvre<sup>1</sup>, Khaddouj Benmoussa<sup>1</sup>, Philippe Batigne<sup>1</sup>, Agnès Aubouy<sup>1</sup>, Johan Auwerx<sup>2</sup>, Sylvain Kirzin<sup>3</sup>, Delphine Bonnet<sup>4,5</sup>, Marie Danjoux<sup>6</sup>, Bernard Pipy<sup>1</sup>, Laurent Alric<sup>1,4,9</sup>, Hélène Authier<sup>1,9,\*</sup> and Agnès Coste<sup>1,7,9</sup>

**Affiliations:**

<sup>1</sup>UMR 152 Pharma Dev, Université de Toulouse, IRD, UPS, France

<sup>2</sup>Metabolic signaling, Institute of Bioengineering, Ecole Polytechnique Fédérale de Lausanne, Lausanne 1015, Switzerland

<sup>3</sup>Department of Surgery and Digestive Diseases, CHU Purpan, Université de Toulouse, France

<sup>4</sup>Department of Internal Medicine and Digestive Diseases, CHU Purpan, Toulouse, France

<sup>5</sup>IRSD, Université de Toulouse, INSERM, INRA, ENVT, UPS, Toulouse, France

<sup>6</sup>Department of Pathology, CHU Purpan, Université de Toulouse, France

<sup>7</sup>Lead contact

<sup>8</sup>These authors contributed equally to this work

<sup>9</sup>These authors are co-senior authors

\*Corresponding author: [helene.authier@univ-tlse3.fr](mailto:helene.authier@univ-tlse3.fr)

## SUMMARY

Colonic macrophages are considered as major effectors of inflammatory bowel diseases (IBD), and the control of gut inflammation through C-type lectin receptors is an emerging concept. We show that during colitis the loss of Dectin-1 on myeloid cells prevents intestinal inflammation, while the lack of MR exacerbates it. A marked increase in Dectin-1 expression in DSS-exposed MR-deficient mice, support the critical contribution of Dectin-1 in colitis outcome. Dectin-1 is crucial for Ly6C<sup>high</sup>CCR2<sup>high</sup> monocyte population enrichment in the blood and their recruitment to inflamed colon as precursors of inflammatory macrophages. Dectin-1 also promotes inflammasome-dependent IL1 $\beta$  secretion through the leukotriene B4 production. Interestingly, the colonic inflammation is associated with a concomitant overexpression of Dectin-1/CCL2/LTA4H and a down-regulation of MR on macrophages from IBD patients. Thus, MR and Dectin-1 on macrophage are important mucosal inflammatory regulators during intestinal inflammation. Finally, this study offers breakthroughs on the mechanism may contribute to pathogenesis of intestinal inflammation.

## INTRODUCTION

Crohn's disease (CD) and ulcerative colitis (UC) are chronic inflammatory bowel diseases (IBD) caused by a combination of intestinal dysbiosis, increased intestinal mucosal permeability to gut bacteria and inappropriate immunomodulatory response. Genetic or environmental factors also contribute to the pathogenesis of this disease.

Macrophages (M $\phi$ ) represent the most abundant mononuclear phagocytic population in the *lamina propria* of the intestine, and are essential for local homeostasis and for maintaining a balance between the commensal microbiota and the host (Bain and Mowat, 2014). The selective inertia of intestinal M $\phi$  is one of the principal mechanisms preventing inappropriate reactions to commensal microbes. These tissue-resident intestinal M $\phi$  act as non-inflammatory scavengers of microbes and they also assist in the maintenance of regulatory T (Treg) cells and promote epithelial cell renewal (Bain and Mowat, 2014; Kühl et al., 2015).

In IBD, M $\phi$  massively infiltrate the intestinal mucosae and these newly recruited activated M $\phi$  are thought to be major contributors to the production of inflammatory cytokines, thus playing a central role in the pathogenesis of IBD (Neurath, 2014). Several lines of evidence support the role of inflammatory M $\phi$  in the IBD pathogenesis. In addition to the increased presence of inflammatory-polarized M $\phi$  in the *lamina propria*, studies have shown that these M $\phi$  directly contribute to the defective intestinal barrier function in subjects with IBD (Lissner et al., 2015) by secreting pro-inflammatory mediators such as tumor necrosis factor  $\alpha$  (TNF $\alpha$ ), IL1, IL6, IL8, IL12, IL18, arachidonic acid (AA) metabolites, and reactive oxygen or nitrogen species (Bain and Mowat, 2014; Lissner et al., 2015). Because intestinal M $\phi$  display a rather short half-life, a continuous replenishment by blood monocytes is required. In IBD, inflammatory Ly6C<sup>high</sup>CCR2<sup>high</sup> monocytes are recruited from the blood to the *lamina propria* to promote inflammation (Zigmond et al., 2012; Grainger et al., 2017). In tissues, Ly6C<sup>high</sup>CCR2<sup>high</sup> and Ly6C<sup>low</sup>CCR2<sup>low</sup> monocytes are generally thought to undergo preferential differentiation into inflammatory M $\phi$  and anti-inflammatory M $\phi$ , respectively (Yang et al., 2014).

Pathogen recognition receptors (PPR) play a crucial role in maintaining the fine balance between immune tolerance to commensal microbes and uncontrolled innate activation leading to inflammation and, subsequently, to IBD pathogenesis. Among the PRR, some C-type lectin receptors (CLR), such as Dectin-1, mannose receptor (MR) and dendritic cell-specific intercellular adhesion molecule-3-grabbing non-integrin (DC-SIGN) have been found to be involved in the IBD pathogenesis (Heinsbroek et al., 2012; Iliev et al., 2012; Liu et al., 2008; Saunders et al., 2010; Sokol et al., 2016; Tang et al., 2015). Although Dectin-1 is the most investigated, its role in the control of gut inflammation remains questionable. On one hand, it has been shown that Dectin-1-deficient mice develop more severe dextran sulfate sodium (DSS)-induced colitis. This was accompanied by mycobiota changes and by overgrowth of opportunist species, demonstrating that this phenotype was dependent on the inability of Dectin-1-deficient mice to control fungal invasion during colitis. This study suggest that host impaired antifungal immunity is involved in the development of gut inflammation (Iliev and Leonardi, 2017; Iliev et al., 2012; Leonardi et al., 2018).

On the other hand, Dectin-1-deficient mice were refractory to experimental colitis in the absence of opportunistic fungi due to an increase in *Lactobacillus murinus* in the gut commensal microflora that triggers the expansion of Treg cells (Tang et al., 2015). Thus, although several lines of evidence support the role of Dectin-1 in the production of inflammatory mediators (Galès et al., 2010; Lefèvre et al., 2013), the composition of the fungal gut microbiota could be a determining factor in the pro- or anti-inflammatory effect of Dectin-1 during colitis (Heinsbroek et al., 2012; Iliev and Leonardi, 2017; Iliev et al., 2012; Tang et al., 2015).

Interestingly, it has been shown that subjects with CD display elevated Dectin-1 expression on intestinal M $\phi$ , neutrophils, and other immune cells compared to healthy individuals (de Vries et al., 2009). In contrast to data related to Dectin-1, patients with active CD have a reduced number of M $\phi$  expressing MR (CD68+ CD206+) (Hunter et al., 2010). Moreover, a previous study demonstrated that patients who respond to infliximab therapy exhibit a significant induction of these M $\phi$  that contribute to mucosal healing (Vos et al., 2012). This is supported by a report demonstrating the protective effects of a polysaccharide-targeting MR against diarrhea, colonic inflammation and ulceration in rats with colitis (Liu et al., 2008). In contrast to the protective role of MR, a recent report demonstrated that MR-deficient mice display attenuated intestinal inflammation in experimental colitis. However, this study attributed this effect to a microRNA (miR-511-3p) harbored in intron 5 of the CD206 gene (Heinsbroek et al., 2016).

While the two CLR, Dectin-1 and MR, play a crucial role in pathogen recognition and phagocytosis by M $\phi$ , several studies indicate that they contribute differently to the activation of inflammatory signaling pathways. Indeed, it has been shown that Dectin-1, by recognizing carbohydrates on the surface of pathogens, promotes production of reactive oxygen species (Galès et al., 2010; Lefèvre et al., 2013) and IL1 $\beta$  secretion by M $\phi$  through inflammasome-dependent signaling pathways (Cheng et al., 2011). These findings support the hypothesis that Dectin-1 plays an important role in IBD development, as the NLRP3 inflammasome was identified as a critical mechanism by which M $\phi$  are involved in intestinal inflammation (Bauer et al., 2010). Despite its capacity to participate in inflammatory signaling pathways in response to infections (Coste et al., 2003; Galès et al., 2010),

MR has also been shown to dampen inflammation and to inhibit Th1-polarized immune responses (Chieppa et al., 2003).

In the present study, we identify Dectin-1 on M $\phi$  as an important regulator of the mucosal inflammatory response during intestinal inflammation. Dectin-1, through CCL2 production, promotes the infiltration of Ly6C<sup>high</sup>CCR2<sup>high</sup> monocyte subset from the blood to the inflamed colon as precursor of inflammatory M $\phi$ . Dectin-1 also mediates inflammasome-dependent IL1 $\beta$  secretion through the control of LTB4 production. Finally, we demonstrate that intestinal inflammation occurring in subjects with IBD is associated with Dectin-1 induction and MR downregulation on M $\phi$ , highlighting the relevant role of these CLR on M $\phi$  in the IBD pathogenesis in humans.

## RESULTS

### **Dectin-1 and MR have distinct contributions to the pathogenesis of colitis**

To explore whether Dectin-1 and MR on myeloid compartment participate in the development of DSS-induced colitis, we evaluated intestinal inflammatory responses and mucosal injury in Dectin-1- or MR-conditionally-deficient (LysM-Cre/Dectin-1 L2/L2 mice (Dectin-1<sup>-/-</sup>) or LysM-Cre/MR L2/L2 mice (MR<sup>-/-</sup>)) mice, in which the *Clec7a* or *Mrc-1* gene were selectively disrupted in myeloid-derived cells, and their corresponding WT littermates (STAR method and Figure S1). Compared to WT mice exposed to DSS, weight loss was significantly lower in the DSS-exposed myeloid-specific Dectin-1<sup>-/-</sup> mice (Figure 1A). Macro- and microscopic scores, and colonic MPO activity (Figure 1B), a marker of neutrophil and M $\phi$  infiltrations, were consistently and significantly reduced in the colons of DSS-exposed Dectin-1<sup>-/-</sup> mice compared to those in the colons of their DSS-exposed WT littermates. The reduced inflammation in the colons of Dectin-1<sup>-/-</sup> mice was characterized by a decrease in glandular ulceration, fewer inflammatory infiltrates and the absence of necrotic regions (Figure 1J), highlighting Dectin-1 as a susceptibility factor for colitis. By contrast, weight loss increased significantly in the DSS-exposed MR<sup>-/-</sup> mice compared to their DSS-exposed WT littermates (Figure 1D). Consistent with this finding, the DSS-exposed MR<sup>-/-</sup> mice displayed a higher degree of colonic inflammation, as reflected by an elevated macro- and microscopic scores, higher MPO activity

(Figure 1E), extensive inflammatory infiltrates associated with glandular ulceration and the loss of crypts, and hypersecreting appearance of the adjacent glands (Figure 1J), suggesting a protective role of MR against colitis. While the mild colonic inflammation in the DSS-exposed Dectin-1<sup>-/-</sup> mice was associated with low levels of the pro-inflammatory cytokines IL6 and IL1 $\beta$  in the colon (Figure 1C), the exacerbated colonic inflammation observed in the DSS-exposed MR<sup>-/-</sup> mice was related to the excessive secretion of these cytokines (TNF $\alpha$ , IL6 and IL1 $\beta$ ) (Figure 1F). The severity of colitis resulted in a significantly higher survival rate of Dectin-1<sup>-/-</sup> mice and lower survival rate of MR<sup>-/-</sup> mice compared with their WT littermates, supporting a role for Dectin-1 and MR in colitis outcome (Figure 1K). The role of Dectin-1 and MR in the development of colitis was further supported in another TNBS-induced colitis murine experimental model (Figure S2). Remarkably, the use of a mouse model deficient in both Dectin-1 and MR in myeloid-derived cells demonstrated that these DSS-exposed mice exhibited less severe inflammation than WT, as demonstrated by reduced weight loss (Figure 1G), decreased macroscopic and microscopic scores, MPO activity (Figure 1H) and TNF $\alpha$ , IL6 and IL1 $\beta$  levels in the colons (Figure 1I). These data are similar to that observed in DSS-exposed Dectin-1<sup>-/-</sup> mice and highlight a greater role of Dectin-1 compared to MR in the development of colitis.

We then thoroughly investigated the mucosae-associated fungal and bacterial colonization of unexposed or DSS exposed-Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice and their WT littermates (Figure S3A, B). Although no significant difference was observed in the fungal and bacterial content between Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice and their WT littermates, as expected, DSS treatment increases pro-inflammatory fungal burden from *Candida sp.* and pro-inflammatory bacterial burden from *Bacteroidetes* and *Enterobacteria* phylum (Ohkusa and Koido, 2015). In Dectin-1<sup>-/-</sup> mice, reduced severity of colitis was associated with a decrease in the content of pro-inflammatory bacteria (*Bacteroidetes*, *Enterobacteria*) and fungi (*Candida sp.*) and with an increase in protective bacteria (*Firmicutes*, *F. prausnitzii*) (Figure S3A). Inversely, the severity of colitis in MR<sup>-/-</sup> mice correlated with increased *Bacteroidetes*, *Enterobacteria* and *Candida sp.* (Figure S3B).

To evaluate that *Candida* burden may influence the inflammatory phenotype of DSS-treated mice, we evaluated the macroscopic score in DSS-exposed Dectin-1<sup>-/-</sup> mice and their WT littermates after

a gastrointestinal infection with *C. albicans*. *C. albicans* supplementation of Dectin-1<sup>-/-</sup> mice aggravated colitis in response to DSS (Figure S3C), supporting that the absence of Dectin-1 can also promote DSS-induced colitis because of the expansion of pathogenic commensal fungi in the gut (Iliev et al., 2012; Leonardi et al., 2018).

### **Dectin-1 promotes pro-inflammatory polarization of colonic macrophages during colitis**

To establish whether Dectin-1 and MR on myeloid cells influence colonic inflammation, we evaluated the mucosal infiltration of M $\phi$  (CD45<sup>+</sup>, CD11b<sup>+</sup>, F4/80<sup>+</sup>, SiglecF<sup>-</sup>, Ly6G<sup>-</sup>), eosinophils (CD45<sup>+</sup>, F4/80<sup>+</sup>, CD11b<sup>+</sup>, SiglecF<sup>+</sup>, Ly6G<sup>-</sup>), neutrophils (CD45<sup>+</sup>, F4/80<sup>-</sup>, CD11b<sup>+</sup>, Ly6G<sup>+</sup>, SiglecF<sup>-</sup>), T and B cells (CD45<sup>+</sup>, CD3<sup>+</sup> and CD45<sup>+</sup>, CD19<sup>+</sup>) in colonic tissues from DSS-exposed Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice (Figure S4, Figure 2A). As expected, DSS induced significant M $\phi$ , eosinophil, neutrophil and T cell infiltration in the colonic mucosae of WT mice (Figure 2A). Interestingly, although mucosal M $\phi$  infiltration was reduced in DSS-exposed Dectin-1<sup>-/-</sup> mice, the DSS-exposed MR<sup>-/-</sup> mice displayed increased M $\phi$  proportion in the colonic mucosae. Moreover, the frequency of eosinophils, neutrophils, T and B cells in colonic mucosa was not altered both in DSS-exposed Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice. These data suggest that only M $\phi$  recruitment in colon during colitis is dependent on the expression of Dectin-1 or MR.

Interestingly, the clodronate-containing liposomes *i.p.* administration in mice, leading to a selective depletion of M $\phi$  (Figure S5), decreased the macroscopic score both in Dectin-1<sup>-/-</sup>, MR<sup>-/-</sup> mice and their WT littermates, supporting the critical involvement of M $\phi$  in the development of colitis (Figure 2B).

Inflammatory activity in colitis is closely dependent on the polarization state of M $\phi$ . To further explore whether Dectin-1 and MR influence the phenotype of recruited M $\phi$ , we analyzed M $\phi$  populations present in colonic tissues from Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice following DSS treatment. As depicted in figure 2C and D, a large number of the colonic-resident M $\phi$  in the non-DSS-exposed WT, Dectin-1<sup>-/-</sup>, and MR<sup>-/-</sup> mice exhibited a CD11b<sup>low</sup> and CD209<sup>+</sup> anti-inflammatory phenotype. In the colons of DSS-exposed WT mice, the proportion of CD11b<sup>high</sup> and CD209<sup>-</sup> pro-inflammatory M $\phi$



increased significantly. Interestingly, whereas the induction of the proportion of CD11b<sup>high</sup> and CD209<sup>+</sup> M $\phi$  in DSS-exposed WT mice was greatly reduced in the Dectin-1<sup>-/-</sup> mice, it increased substantially in the MR<sup>-/-</sup> mice, demonstrating that the severity of colitis is related to the distinct pro-inflammatory M $\phi$  population.

To assess the role of Dectin-1 and MR in M $\phi$  activation during the development of colonic inflammation, we evaluated the gene expression of pro- and anti-inflammatory markers and specific classical and alternative activation markers in colonic M $\phi$  from DSS-exposed Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice (Figure 3). Overall, M $\phi$  from DSS-treated WT mice displayed an up-regulation of pro-inflammatory cytokines, such as *Tnf $\alpha$* , *Il1 $\beta$* , *Il6* and *Il12p40*. In line, Chemokine ligand 2 (*Ccl2*), Fc $\gamma$  receptor *Fcgr3* (Cd16), *Fcgr1* (Cd64), co-stimulatory protein *Cd86*, chemokine receptor 2 (*Ccr2*), inducible nitric oxide synthase (*Nos2*) and *p47<sup>phox</sup>* (a cytosolic subunit of the NADPH oxidase complex) pro-inflammatory factors were also upregulated (Figure 3A and B). Consistent with the reduced susceptibility of Dectin-1<sup>-/-</sup> mice to colitis, the transcriptional induction of pro-inflammatory markers upon DSS treatment was reduced in the M $\phi$  from Dectin-1<sup>-/-</sup> mice (Figure 3A). In contrast, with the more severe colonic inflammation in MR<sup>-/-</sup> mice, colonic M $\phi$  displayed a robust expression of inflammatory markers (Figure 3B). Thus, more pronounced colonic inflammation was associated with the presence of colonic M $\phi$  that expressed high levels of pro-inflammatory markers, highlighting that the polarization state of M $\phi$  is critical for colitis development. Next, we evaluated the expression of anti-inflammatory and specific alternative markers. DSS treatment did not alter the expression of *Il10*, *Tgf- $\beta$* , *Cd36*, *Mrc-1* (MR), *Cd209*, *Arginase-1*, and *Fizz-1* (Figure 3A and B). Only *Clec7a* (Dectin-1) increased significantly in the DSS-exposed WT mice, and its expression was amplified in MR<sup>-/-</sup> mice (Figure 3B), further supporting the significant contribution of Dectin-1 to the development of colonic inflammation.

**Dectin-1 mediates the infiltration of the Ly6C<sup>high</sup>CCR2<sup>high</sup> monocyte subset from the blood to the inflamed colon as inflammatory macrophage precursors**

The inflammatory Ly6C<sup>high</sup>CCR2<sup>high</sup> monocytes in the blood selectively traffic to sites of injury to promote inflammation, and once within the tissues, they differentiate into inflammatory M $\phi$  (Yang et al., 2014; Zigmond et al., 2012). To elucidate whether the Dectin-1-mediated inflammatory phenotype in colonic M $\phi$  was accompanied by a specific phenotypic profile of blood monocytes, the characterization of monocyte subsets was performed in DSS-exposed Dectin-1<sup>-/-</sup> or MR<sup>-/-</sup> mice (Figure 4A). As expected, DSS induced a significant increase in the inflammatory Ly6C<sup>high</sup>CD43<sup>low</sup>CCR2<sup>high</sup> monocyte subset in the blood of WT mice. Interestingly, this augmentation was reduced in DSS-exposed Dectin-1<sup>-/-</sup> mice, whereas it was amplified in DSS-exposed MR<sup>-/-</sup> mice. The proportion of the anti-inflammatory Ly6C<sup>low</sup>CD43<sup>high</sup>CCR2<sup>low</sup> monocyte subset was not altered in DSS-exposed WT or deficient mice (Figure 4A).

Consistent with the increase in the Ly6C<sup>high</sup>CCR2<sup>high</sup> monocyte subset in DSS-exposed mice, we observed an elevated amount of CCL2 (the major chemokine driving Ly6C<sup>high</sup>CCR2<sup>high</sup> monocyte recruitment from the bone marrow to the bloodstream, and to the sites of inflammation) level in the colon (Figure 4B). Moreover, the amount of CCL2 decreased in DSS-exposed Dectin-1<sup>-/-</sup> mice and increased in DSS-exposed MR<sup>-/-</sup> mice relative to that in DSS-exposed WT mice, suggesting that Dectin-1-mediated CCL2 production in the colon during colitis is involved in the enrichment of the Ly6C<sup>high</sup>CCR2<sup>high</sup> population in the blood, and in the recruitment of these inflammatory M $\phi$  precursors to inflamed intestinal tissues.

To further confirm the involvement of Dectin-1 or MR in the recruitment of M $\phi$  into colonic mucosae from the blood monocytes during colitis, CD45.1 recipient mice were transferred with sorted monocytes isolated from CD45.2 donor Dectin-1<sup>-/-</sup> or MR<sup>-/-</sup> mice and their WT littermates (Figure 4C). Interestingly, the percentage of CD45.2 M $\phi$  in the colon of CD45.1 recipient mice was strongly decreased when the transferred monocytes were derived from Dectin-1<sup>-/-</sup> mice (Figure 4D). Conversely, when the transferred monocytes were derived from CD45.2 MR<sup>-/-</sup> mice, the percentage of CD45.2 M $\phi$  in colonic mucosae of CD45.1 recipient mice was robustly increased, supporting the involvement of Dectin-1 and MR in the recruitment of colonic M $\phi$  derived from blood monocytes during colitis.

To determine the capacity of activation of M $\phi$  derived from monocytes recruited in colon during colitis, the gene expression of pro- and anti-inflammatory and specific classical and alternative activation markers were evaluated in colonic CD45.2 cells isolated from CD45.1 recipient mice (Figure 4C). Remarkably, mRNA levels of *Tnf $\alpha$* , *Il1 $\beta$* , *Il6*, *Il12p40*, *Ccl2*, *Fcgr1*, *Ccr2*, *Nos2* and *p47<sup>phox</sup>* pro-inflammatory markers were decreased in CD45.2<sup>+</sup> cells from CD45.1 recipient mice transferred with monocytes from Dectin-1<sup>-/-</sup> mice (Figure 4E). Inversely, the CD45.2<sup>+</sup> cells from CD45.1 recipient mice transferred with monocytes from MR<sup>-/-</sup> mice displayed an up-regulation of pro-inflammatory markers (Figure 4F). Interestingly, *Clec7a* expression was strongly increased in CD45.2<sup>+</sup> cells from CD45.1 recipient mice transferred with monocytes from MR<sup>-/-</sup> mice (Figure 4F), further supporting the critical contribution of Dectin-1 in the activation of colonic M $\phi$  toward an inflammatory phenotype.

Therefore, altogether these experiments confirm that Dectin-1 contributes both in Ly6C<sup>high</sup>CCR2<sup>high</sup> monocyte population enrichment in the blood, their recruitment to inflamed colon as precursors of colonic M $\phi$  and in the activation of these M $\phi$  toward an inflammatory profile.

### **Dectin-1 is critical in the 5-lipoxygenase/LTA4H-mediated leukotriene B4 (LTB4) production during colitis**

As one of the most important mediators of IBD, AA metabolites (including prostaglandins and leukotrienes) are essential to the development of colonic inflammation. Because the major pathways for AA metabolism that are relevant for IBD include COX-1/COX-2 cyclooxygenases, 5-LOX, and 12/15-LOX, their expression was evaluated in the colonic M $\phi$  from DSS-exposed Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice (Figure 5A). The COX-2 mRNA level was strongly induced in the M $\phi$  from DSS-exposed WT mice, while it remained unaffected in the M $\phi$  from DSS-exposed Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice (Figure 5A). Although the mRNA levels of 5-LOX (*Alox5*) and 12/15-LOX (*Alox15*) were increased substantially in the M $\phi$  from DSS-exposed WT mice, their expression was significantly decreased in the M $\phi$  from DSS-exposed Dectin-1<sup>-/-</sup> mice and unaltered in the M $\phi$  from DSS-exposed MR<sup>-/-</sup> mice (Figure 5A). In line with reduced 5-LOX and 12/15-LOX gene expression in the M $\phi$  from DSS-

exposed Dectin-1<sup>-/-</sup> mice, the mRNA expression of LTA4 hydrolase (*Lta4h*), which controls LTB4 production, was decreased substantially. Accordingly, LTB4 production was completely abrogated in the colons of DSS-exposed Dectin-1<sup>-/-</sup> mice (Figure 5B). Conversely, the mRNA level of LTA4H was substantially increased in the Mφ from DSS-exposed MR<sup>-/-</sup> mice (Figure 5A), correlating with the augmented LTB4 levels (Figure 5B). Consistent with the altered LTB4 production in Mφ from DSS-exposed Dectin-1<sup>-/-</sup> mice, the LTB4 receptors BLT1 and BLT2 remained poorly expressed (Figure 5A). Inversely, the mRNA levels of both BLT1 and BLT2 increased in Mφ from DSS-exposed MR<sup>-/-</sup> mice (Figure 5A). Furthermore, although DSS treatment resulted in the induction of AA secretion by WT and MR<sup>-/-</sup> Mφ, it failed to do so in Dectin-1<sup>-/-</sup> Mφ (Figure 5C). Altogether, these data indicate that Dectin-1 is critical for the mobilization of AA and for the regulation of 5-LOX and LTA4H, supporting the importance of Dectin-1 in the control of LTB4 production during colitis.

### **Dectin-1 mediates inflammasome-dependent IL1β secretion through the control of LTB4 production**

Considering the involvement of Dectin-1 and MR in the regulation of LTB4 production in Mφ during colitis and the importance of LTB4 in inflammasome-dependent IL1β release (Amaral et al., 2012), we next evaluated the role of LTB4 in the control of IL1β production in Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> Mφ (Figure 6). These Mφ were primed with LPS, mannan and (1, 3)-β-glucans (zymosan) *in vitro* to trigger transcription of pro-IL1β and then stimulated with DSS, a potassium ionophore activating caspase-1, which is involved in the proteolytic processing of pro-IL1β (Bauer et al., 2010). As depicted in figure 6A, LTB4 production was strongly increased in LPS-primed WT Mφ exposed to DSS compared to resident Mφ. This induction was totally abolished in LPS-primed Dectin-1<sup>-/-</sup> Mφ exposed to DSS, while it was improved in LPS-primed MR<sup>-/-</sup> Mφ exposed to DSS. These results support the major role of Dectin-1 in the control of LTB4 production by Mφ. Although IL1β production was not affected in LPS-primed *Alox15*<sup>-/-</sup> Mφ exposed to DSS, it was strongly decreased in the *Alox5*<sup>-/-</sup> Mφ (Figure 6B). Interestingly, the addition of LTB4 restored IL1β secretion in *Alox15*<sup>-/-</sup> Mφ, supporting the importance of 5-LOX-mediated LTB4 production in IL1β generation during colonic

inflammation. While the addition of exogenous LTB<sub>4</sub> efficiently restored IL1 $\beta$  production in LPS-primed Dectin-1<sup>-/-</sup> M $\phi$  exposed to DSS, it did not affect IL1 $\beta$  secretion by MR<sup>-/-</sup> M $\phi$  (Figure 6C). These data clearly demonstrate the critical role for Dectin-1 and MR in LTB<sub>4</sub>-mediated IL1 $\beta$  production.

The use of a specific caspase-1 inhibitor Z-YVAD revealed that the secretion of IL1 $\beta$  by LPS-primed M $\phi$  exposed to DSS was dependent on caspase-1 activation as demonstrated by an inability of WT, Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> M $\phi$  to produce IL1 $\beta$  (Figure 6C). Moreover, the processing of pro-caspase-1 into its p10 subunit, which is a hallmark of caspase-1 activation, was also determined in LPS-primed Dectin-1<sup>-/-</sup> or MR<sup>-/-</sup> M $\phi$  exposed to DSS (Figure 6D). The level of p10 subunit was significantly increased in WT M $\phi$ . Interestingly, while the level of p10 subunit was diminished in Dectin-1<sup>-/-</sup> M $\phi$ , it was still elevated in MR<sup>-/-</sup> M $\phi$ , suggesting that Dectin-1 induces caspase-1 activation to secrete IL1 $\beta$ . Therefore, Dectin-1 mediates inflammasome-dependent IL1 $\beta$  secretion by controlling LTB<sub>4</sub> production during colitis.

### **Dectin-1, CCL2 and LTA4H overexpression and MR down-regulation are related to colonic inflammation grade in IBD subjects**

Based on the observation that Dectin-1<sup>-/-</sup> mice are less susceptible and MR<sup>-/-</sup> mice are more susceptible to the development of colitis, we next analyzed the mRNA expression of Dectin-1 (*Clec7a*), MR (*Mrc-1*) and LTA4H (*Lta4h*) in colonic biopsies from healthy subjects and biopsies taken from healthy and inflamed mucosae of CD and UC subjects (Figure 7A). As expected, the inflamed intestines of IBD pathologies showed an increase in the pro-inflammatory markers TNF $\alpha$  (*Tnfa*) and IL1 $\beta$  (*Il1b*) relative to the macroscopically and histologically healthy intestine (Figure S6). Interestingly, Dectin-1 mRNA levels increased considerably in inflamed colonic biopsies from both CD and UC subjects, compared with those in biopsies from healthy subjects and from healthy-looking mucosae. This was accompanied with a reduction in MR levels (Figure 7A). Accordingly, the percentage of Dectin-1<sup>+</sup> M $\phi$  (CD64<sup>+</sup> Dectin-1<sup>+</sup>) increased substantially and the percentage of MR<sup>+</sup> M $\phi$  (CD64<sup>+</sup> CD206<sup>+</sup>) decreased in the colonic mucosae of IBD subjects compared to healthy

subjects (Figure 7B). Consistent with the elevated Dectin-1 and reduced MR expression in inflamed colonic biopsies from subjects with IBD, the mRNA expression of CCL2 and LTA4h strongly increased (Figure 7A). Additionally, the protein level of CCL2 and the LTB4 release robustly increased in the colonic mucosae of IBD subjects (Figure 7C). Therefore, the intestinal inflammation occurring in IBD in humans is associated with a specific induction of Dectin-1, CCL2, and LTB4 and a reduction in MR expression, suggesting that this mechanism may contribute to the pathogenesis of IBD in humans.

## DISCUSSION

The regulation of intestinal immunity through the activation of CLR on M $\phi$  is an emerging concept in IBD pathogenesis understanding. Here, we report that mice deficient in Dectin-1-deficient mice in myeloid-derived cells have a decreased susceptibility to colitis with a significant reduction in colonic inflammatory parameters in two independent models of colitis, highlighting the pro-inflammatory function of Dectin-1 in M $\phi$ . This finding is in accordance with reports showing that Dectin-1 can be involved in the aggravation of intestinal inflammation in the absence of opportunistic fungi in the gut (Tang et al., 2015), and that orally administered  $\beta$ -glucans aggravate DSS-induced intestinal inflammation (Heinsbroek et al., 2015). Moreover, in line with previous data showing that the absence of Dectin-1 can also promote DSS-induced colitis because of the expansion of pathogenic commensal fungi in the gut (Iliev et al., 2012; Leonardi et al., 2018), our study demonstrated that *C. albicans* supplementation aggravates colitis in Dectin-1<sup>-/-</sup> mice (Figure S3C), demonstrating that Dectin-1-deficiency can affect host anti-fungal immunity and hence stimulates inflammatory responses in the gut. Thus, Dectin-1 can influence the development of colitis by directly triggering inflammatory signaling pathways but also by contributing to the control of fungal and bacterial microbiota.

Interestingly, the selective deletion of Dectin-1 in myeloid-cells and the decrease of colonic inflammation in M $\phi$  depleted-mice by clodronate excluded the contribution of other Dectin-1-expressing cells, such as intestinal epithelial cells and other Dectin-1-expressing immune cells.

Altogether, these results establish a direct link between the expression of Dectin-1 on M $\phi$  and the colonic inflammatory status.

In contrast to Dectin-1<sup>-/-</sup> mice, MR<sup>-/-</sup> mice developed more severe colonic inflammation, highlighting the divergent roles of these CLR in the inflammatory response during colitis. Consistent with the protective effect for MR against colonic inflammation, the treatment of TNBS-exposed rats with a polysaccharide-targeting MR significantly reduced diarrhea, colonic inflammation and ulceration (Liu et al., 2008). Moreover, in conjunction with more severe colonic inflammation in DSS-exposed Dectin-1<sup>-/-</sup> mice, we showed a marked increase in Dectin-1 expression in M $\phi$ , suggesting that the greater extent of intestinal inflammation in MR<sup>-/-</sup> mice could be mediated by Dectin-1. In support of the critical role of Dectin-1 in the development of colonic inflammation in DSS-exposed MR<sup>-/-</sup> mice, a similar decrease in inflammation was observed in mice with Dectin-1 or both Dectin-1 and MR deficiencies in myeloid-derived cells. Consistent with these results, our findings in clinical samples showed that the intestinal inflammation occurring in IBD subjects is associated with a specific increase of Dectin-1 expression and a reduction in MR expression on M $\phi$ . This correlates with reports demonstrating elevated Dectin-1 expression in M $\phi$  of actively inflamed colonic tissues relative to non-inflamed tissues (de Vries et al., 2009). This is also supported by a reduced number of M $\phi$  expressing MR in subjects with active CD (Hunter et al., 2010). Thus, these data reinforce our findings, thereby highlighting Dectin-1 in M $\phi$  as a crucial susceptibility factor in the development of intestinal inflammation and demonstrating the preponderant contribution of Dectin-1 relative to MR.

In this report, in accordance with the well-established role of inflammatory M $\phi$  in the pathogenesis of IBD (Hunter et al., 2010; Lin et al., 2014; Lissner et al., 2015), we showed that Dectin-1 could contribute to colitis pathogenesis by promoting the inflammatory polarization of colonic M $\phi$ . The involvement of Dectin-1 as an inducer of inflammatory M $\phi$  differentiation in the colon was supported by a previous report showing that the absence of Dectin-1 during pulmonary paracoccidioidomycosis impairs M1 differentiation while promoting M2-like phenotype (Loures et al., 2014). Interestingly, we also demonstrated that the increase in Dectin-1-dependent inflammatory M $\phi$  recruitment in the colon was associated with both the augmentation of the Ly6C<sup>high</sup>CCR2<sup>high</sup>

monocyte subset in the blood and CCL2 production in the gut. Accordingly, CCL2 was described as the major chemokine driving Ly6C<sup>high</sup>CCR2<sup>high</sup> monocyte recruitment from the bone marrow into the circulatory system and to the inflammation sites (Yang et al., 2014; Zigmond et al., 2012). Moreover, this monocyte subset is known to preferentially differentiate into inflammatory M $\phi$  in tissues (Yang et al., 2014). These data provide evidence that Dectin-1 plays a critical role in CCL2 production by M $\phi$ , which is involved in the recruitment of Ly6C<sup>high</sup>CCR2<sup>high</sup> monocytes as inflammatory M $\phi$  precursors during colitis. Thus, we have revealed a mechanism whereby Dectin-1 regulates intestinal inflammation by promoting inflammatory monocyte recruitment and M $\phi$  differentiation.

Because Dectin-1 is involved in M $\phi$  differentiation toward inflammatory phenotype and because caspase-1-dependent IL1 $\beta$  secretion is strongly upregulated in inflammatory M $\phi$  (Pelegriin and Surprenant, 2009), the loss of Dectin-1 during colitis compromised the ability of the M $\phi$  to produce IL1 $\beta$  due to impaired caspase-1 activation. This is in agreement with reports showing that Dectin-1 can act as an extracellular sensor for pathogens to induce IL1 $\beta$  release through inflammasome-dependent signaling pathways (Cheng et al., 2011; Lefèvre et al., 2013; van de Veerdonk et al., 2009). Thus, in line with the fact that the inflammasome has been identified as a critical mechanism mediating intestinal inflammation in the DSS-induced colitis model (Bauer et al., 2010) and that IL1 $\beta$  levels correlate with the severity of IBD (Mao et al., 2018; McAlindon et al., 1998), we showed that Dectin-1 participates in IBD development by positively controlling inflammasome-dependent IL1 $\beta$  secretion in colonic M $\phi$ . Although many studies have shown that IL1 $\beta$  contributes to the development of inflammation in colitis (Mao et al., 2018) depending on genetic and environmental factors, IL1 $\beta$  can also participate in tissue repair, and thus, contribute to the healing of intestinal lesions (Bersudsky et al., 2014; Dupaul-Chicoine et al., 2010). Thus, IL1 $\beta$  can play a dual role depending on intestinal state. First, this cytokine participates in the triggering of the inflammation, and then, in condition of active inflammation, it is required for tissue repair.

In addition to the key role of Dectin-1 on M $\phi$  in caspase-1-dependent IL1 $\beta$  secretion during colitis, this study also provides mechanistic insights into the link between this CLR and inflammasome activation. Our findings showing both impaired AA mobilization and LTB<sub>4</sub> production in M $\phi$  from



DSS-exposed Dectin-1<sup>-/-</sup> mice substantiate the importance of Dectin-1 in the control of LTB<sub>4</sub> production during colitis. This observation is consistent not only with our results showing that the gene expression of 5-LOX and LTA<sub>4</sub> hydrolase (whose enzymatic activity is critical for LTB<sub>4</sub> synthesis) is down-regulated in M $\phi$  of DSS-exposed Dectin-1<sup>-/-</sup> mice, but also with the known capacity of Dectin-1 to activate AA secretion in response to the  $\beta$ -glucan component of yeasts (Suram et al., 2006). Furthermore, the restoration of IL1 $\beta$  production in DSS-exposed Dectin-1<sup>-/-</sup> M $\phi$  by exogenous LTB<sub>4</sub> highlights the critical role of Dectin-1 in LTB<sub>4</sub>-mediated IL1 $\beta$  production, which is best supported by the concomitant overexpression of pro-IL1 $\beta$ , Dectin-1, and Lta4h, and the secretion of LTB<sub>4</sub> in clinical biopsies from the mucosae of IBD subjects. Our data are consistent with the results of previous studies demonstrating that subjects with active IBD display significantly higher LTB<sub>4</sub> synthesis, 5-LOX and LTA<sub>4</sub>H expression compared to healthy controls (Jupp et al., 2007). Thus, the identification of the AA/LTB<sub>4</sub>/Dectin-1 axis in activating IL1 $\beta$  secretion in M $\phi$  during gut inflammation represents a major breakthrough in the understanding of intestinal innate immune responses during colitis.

In conclusion, we have shown that Dectin-1 gene deletion in M $\phi$  prevents intestinal inflammation, whereas the loss of MR results its exacerbation. Interestingly, we demonstrated that the severity of intestinal inflammation in MR<sup>-/-</sup> mice is mediated by Dectin-1 overexpression, further supporting the major contribution of Dectin-1 to colitis development. Dectin-1 mediates inflammatory M $\phi$  recruitment in the colon through CCL2 production, responsible for the infiltration of the Ly6C<sup>high</sup>CCR2<sup>high</sup> monocyte subset. Our findings also revealed a Dectin-1-coupled signaling pathway in colonic M $\phi$  that controls intestinal inflammation by positively controlling inflammasome-dependent IL1 $\beta$  secretion *via* the regulation of LTB<sub>4</sub> production. All of these results are reinforced by increased CD64<sup>+</sup> Dectin-1<sup>+</sup> M $\phi$  in colonic mucosae from IBD subjects associated with a higher intestinal CCL2 level and the concomitant up-regulation of IL1 $\beta$ , Dectin-1, LTA<sub>4</sub>H expression and LTB<sub>4</sub> secretion. Finally, this study has relevance and provides important insights into the pathogenesis of inflammatory diseases of the bowel and into the role of Dectin-1 and MR in M $\phi$

during intestinal inflammation and mucosal immunity. Our study could set the stage for further development of therapeutic strategies to control the imbalanced inflammatory response in the gut.

## **ACKNOWLEDGMENTS**

This work was supported by BIOASTER investment, funding from the French government (Agence Nationale pour la Recherche-ANR) through the “programme d’Investissement d’Avenir “grant n°ANR-10-AIRT-03”. This work was sponsored by the University Hospital of Toulouse for regulatory and ethic submission, and by a grant from the Délégation Régionale à la Recherche Clinique des Hôpitaux de Toulouse “MICILIP trial 2013 Clinical trials.gov NCT01990716”. This work was supported by the Fondation pour la Recherche Médicale (FRM grant number ECO20170637477 to GJ). We thank Alexia Zakaroff-Girard and Elodie Riant (I2MC/TRI platform) for flow cytometry assistance and Dimitri Marsal for technical assistance.

## **AUTHOR CONTRIBUTIONS**

H.A., L.A. and A.C. were involved in the study concept and design and in drafting the manuscript. M.R., G.J., H.A., and A.C. performed, acquired, and analyzed experiments. M.D. and D.B. acquired and analyzed histological data. We thank M.P., E.M., M.A., B.B., L.L., K.B., A.A. and P.B. for technical support and J.A., S.K. and L.A. for material support.

## **DECLARATION OF INTERESTS**

The authors declare no competing interests.

## **FIGURE LEGENDS**

**Figure 1.** Different contributions of Dectin-1 and MR on macrophages in the development of gut inflammation

(A-I) Body weight (A, D, G), macroscopic and microscopic scores, and MPO activity (B, E, H), and TNF $\alpha$ , IL6, IL1 $\beta$  levels (C, F, I) were determined at 8 days in the colons of control or DSS-exposed Dectin-1<sup>-/-</sup>, MR<sup>-/-</sup> and Dectin-1<sup>-/-</sup>-MR<sup>-/-</sup> mice and their WT littermates (n=12 per group). #p $\leq$ 0.05,

## $p \leq 0.01$ , ### $p \leq 0.005$  compared to DSS-exposed corresponding WT littermates. \* $p \leq 0.05$ , \*\* $p \leq 0.01$ , \*\*\* $p \leq 0.005$  compared to respective unexposed mice (control).

(J) H&E staining of representative cross-sections of distal colon from DSS-exposed WT, Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice. (★) Glandular ulceration and loss of colonic epithelium (ep); (✱) hypersecretory appearance of adjacent glands; (▶) inflammatory infiltrate in the *lamina propria* (lp) and submucosae (sm). Data are representative of three independent experiments.

(K) Survival curve of Dectin-1<sup>-/-</sup>, MR<sup>-/-</sup> mice and their WT littermates (n=10 per group) treated with 2% DSS for 6 days. Mice were then followed until day 20. \* $p \leq 0.05$

See also Figure S2.

**Figure 2.** Dectin-1 is involved in the phenotypic differentiation of colonic macrophages toward an pro-inflammatory phenotype during colitis

(A) Percentages of M $\phi$ , eosinophils, neutrophils, T and B cells in the colons of unexposed (control), DSS-exposed Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice and their WT littermates. Among viable cells, M $\phi$  were identified as CD45<sup>+</sup>, CD11b<sup>+</sup>, F4/80<sup>+</sup>, SiglecF<sup>-</sup>, Ly6G<sup>-</sup>, eosinophils (CD45<sup>+</sup>, F4/80<sup>+</sup>, CD11b<sup>+</sup>, SiglecF<sup>+</sup>, Ly6G<sup>-</sup>), neutrophils (CD45<sup>+</sup>, F4/80<sup>-</sup>, CD11b<sup>+</sup>, Ly6G<sup>+</sup>, SiglecF<sup>-</sup>), T and B cells (CD45<sup>+</sup>, CD3<sup>+</sup> and CD45<sup>+</sup>, CD19<sup>+</sup>) by flow cytometry. \* $p \leq 0.05$ , \*\* $p \leq 0.01$ , \*\*\* $p \leq 0.005$  compared to respective unexposed mice (control). ## $p \leq 0.01$  compared to DSS-exposed corresponding WT littermates. Data are representative of three independent experiments.

(B) Macroscopic score of DSS-exposed Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice and WT littermates treated or not with clodronate liposomes. ### $p \leq 0.005$  compared to corresponding WT littermates.  $\alpha p \leq 0.05$ ,  $\alpha\alpha p \leq 0.01$ ,  $\alpha\alpha\alpha p \leq 0.005$  compared to clodronate-exposed mice. See also Figure S4.

(C, D) Representative dot-plot of CD209<sup>+</sup> and CD11b<sup>+</sup> M $\phi$  from the colons of control, DSS-exposed Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice. M $\phi$  were identified as before. Histograms representing the mean values of the percentage of CD11b<sup>high</sup> CD209<sup>-</sup> M $\phi$  and CD11b<sup>low</sup> CD209<sup>+</sup> M $\phi$  in the colons of control, DSS-exposed Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice. Data are representative of three independent experiments.

\* $p \leq 0.05$ , \*\* $p \leq 0.01$ , \*\*\* $p \leq 0.005$  compared to respective unexposed mice (control). # $p \leq 0.05$ , ## $p \leq 0.01$ , ### $p \leq 0.005$  compared to DSS-exposed corresponding WT littermates.

**Figure 3.** Dectin-1 controls inflammatory-specific gene expression of colonic macrophages during colitis

(A, B) Gene expression analysis of inflammatory and anti-inflammatory polarization markers in colonic M $\phi$  from control or DSS-exposed WT and Dectin-1<sup>-/-</sup> (A) or MR<sup>-/-</sup> (B) mice. Data are representative of three independent experiments. \* $p \leq 0.05$ , \*\* $p \leq 0.01$ , \*\*\* $p \leq 0.005$  compared to respective unexposed mice. # $p \leq 0.05$ , ## $p \leq 0.01$ , ### $p \leq 0.005$  compared to DSS-exposed corresponding WT littermates.

**Figure 4.** Dectin-1 enriches the Ly6C<sup>high</sup>CCR2<sup>high</sup> blood monocyte subset through CCL2 production and enhances its recruitment to inflamed colons during colitis

(A) Histograms representing the proportion of CD11b<sup>+</sup>, Ly6C<sup>high</sup>, CD43<sup>low</sup> and CCR2<sup>+</sup> monocytes and CD11b<sup>+</sup>, Ly6C<sup>low</sup>, CD43<sup>high</sup> and CCR2<sup>-</sup> monocytes in the blood of control, DSS-exposed WT, Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice.

(B) CCL2 chemokine production in colons from control, DSS-exposed WT, Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice.

Data are representative of three independent experiments. \* $p \leq 0.05$ , \*\* $p \leq 0.01$ , \*\*\* $p \leq 0.005$  compared to respective unexposed mice (control). # $p \leq 0.05$ , ## $p \leq 0.01$ , ### $p \leq 0.005$  compared to DSS-exposed corresponding WT littermates.

(C) Experimental procedure: CD45.1 mice received DSS for 4 days. CD45.1 recipient mice were injected into the ophthalmic venous sinus with sorted monocytes isolated from CD45.2 donor mice. After 2 days of DSS treatment followed by 2 days with drinking water, mice underwent colon resection and CD45.2<sup>+</sup> cells isolated by enzymatic digestion of colons were analyzed by flow cytometry (D) and sorted from the colon to evaluate mRNA expression (E, F).

(D) Analysis of CD45.2<sup>+</sup> M $\phi$  of DSS-exposed CD45.1 mice injected with monocytes from CD45.2 WT, Dectin-1<sup>-/-</sup> or MR<sup>-/-</sup> mice.

(E, F) Gene expression analysis of inflammatory and anti-inflammatory markers of M $\phi$  in CD45.2 sorted-cells isolated from the colon of CD45.1 mice injected with monocytes from CD45.2 WT, Dectin-1<sup>-/-</sup> (E) or MR<sup>-/-</sup> (F) mice. \*p $\leq$ 0.05, \*\*p $\leq$ 0.01, \*\*\*p $\leq$ 0.005 compared to WT.

**Figure 5.** Dectin-1 induces LTB4 secretion through the control of AA/5-LOX/LTA4H signaling during colitis

(A) Gene expression analysis of major enzymes involved in AA metabolism and LTB4 production in colonic M $\phi$  from control, DSS-exposed WT, Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice.

(B) LTB4 secretion in colons from DSS-exposed WT, Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice.

(C) (<sup>3</sup>H) AA levels in the culture media of LPS-primed WT, Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> M $\phi$  exposed to DSS. Data are representative of three independent experiments. \*p $\leq$ 0.05, \*\*p $\leq$ 0.01, \*\*\*p $\leq$ 0.005 compared to respective unexposed mice (control). #p $\leq$ 0.05, ##p $\leq$ 0.01, ###p $\leq$ 0.005 compared to DSS-exposed corresponding WT littermates.

**Figure 6.** Dectin-1 promotes LTB4-dependent inflammasome activation and IL1 $\beta$  secretion

(A) LTB4 release by LPS-primed WT, Dectin-1<sup>-/-</sup>, and MR<sup>-/-</sup> M $\phi$  exposed to DSS or not.

(B) IL1 $\beta$  release by LPS-primed WT, 12/15-LOX (*Alox15*<sup>-/-</sup>) or 5-LOX (*Alox5*<sup>-/-</sup>) M $\phi$  stimulated or not with DSS. Data are representative of three independent experiments. \*\*p $\leq$ 0.01, \*\*\*p $\leq$ 0.005 compared to respective DSS non-exposed M $\phi$  (control). #p $\leq$ 0.05 compared to DSS-exposed corresponding WT M $\phi$ .

(C) IL1 $\beta$  release by LPS-primed WT, Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> M $\phi$  exposed or not to DSS in the presence of LTB4 or Z-YVAD. \*\*\*p $\leq$ 0.005 compared to respective DSS non-exposed M $\phi$ . Data are representative of three independent experiments. ##p $\leq$ 0.01, ###p $\leq$ 0.005 compared to respective DSS-exposed M $\phi$ .  $\square\square$ p $\leq$ 0.01,  $\square\square\square$ p $\leq$ 0.005 compared to DSS-exposed corresponding WT untreated or LTB4 or Z-YVAD-treated M $\phi$ .

(D) Immunoblot analysis of caspase-1 p10 mature form in the supernatant (SN) and p45 pro-form in the lysate (cells) of LPS-primed WT, Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> M $\phi$  exposed or not to DSS.

**Figure 7.** Severity of colonic inflammation in subjects with IBD is correlated with Dectin-1, CCL2, and LTB4 up-regulation and MR down-regulation

(A) Gene expression analysis of *Clec7a*, *Mrc-1*, *Lta4h* and *Ccl2* in colonic biopsies of healthy individuals (H) (n=9) and in healthy (NI) (n=20) or inflamed (I) (n=20) mucosae of subjects with IBD, CD or UC. Differences were determined by Mann-Whitney test. \*p<0.05, \*\*p<0.01 compared to NI mucosae. #p<0.05, ###p<0.005, ####p<0.001, #####p<0.0001 compared to healthy mucosae.

(B) Flow cytometry analysis of CD64<sup>+</sup> and Dectin-1<sup>+</sup> or CD206<sup>+</sup> cells in the colonic mucosae of healthy individuals (H) (n=7) and subjects with IBD (n=20).

(C) CCL2 and LTB4 levels in the colonic mucosae of healthy individuals (H) (n=4) and subjects with IBD (n=12). Differences were determined by Mann-Whitney test. \*p<0.05, \*\*\*p<0.005, \*\*\*\*p<0.001, \*\*\*\*\*p<0.0001 compared to healthy mucosae.

See also Figure S5

## STAR Methods

### LEAD CONTACT AND MATERIALS AVAILABILITY

Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, Agnès Coste (agnes.coste@univ-tlse3.fr). This study did not produce new unique reagents.

### EXPERIMENTAL MODEL AND SUBJECT DETAILS

#### Mice

All mouse experiments were performed according to protocols approved by the institutional ethics committee (CEEA122) with permit number 5412-2016051917498658 in accordance with European legal and institutional guidelines (2010/63/UE) for the care and use of laboratory animals. All mice were bred in the same facility, and age- and sex-matched WT mice were first co-housed with genetically modified mice just after weaning at 3 weeks old for at least 4 weeks before use. At the start of the experiments, animals weighed (mean±SD) 24±0.36 grams. Animals were housed in 425x266x185 mm cages (Tecniplast, 1291H Type III H, France) and given access to maintenance

food (Global Diet, Harlan, France) and water *ad libitum*. Environmental enrichment included bedding and one hut. The experimenters were blinded to the mice genotype for monitoring animals.

The myeloid-specific Dectin-1<sup>-/-</sup> or MR<sup>-/-</sup> mice have been described earlier (Galès et al., 2010; Lefèvre et al., 2013). The corresponding floxed littermates were used as control in all experiments. To generate MR floxed (MR L2/L2) mice or Dectin-1 floxed (Dectin-1 L2/L2) mice, genomic DNA covering the MR locus or Dectin-1 locus from the 129Sv strain was amplified using high fidelity PCR. The resulting DNA fragments were assembled into the targeting vector that after linearization by NotI was electroporated into 129Sv ES cells. G418-resistant colonies were selected and analyzed for homologous recombination using PCR and Southern blot hybridization. Positive clones were verified using Southern blot hybridization. The genomic DNA was prepared from ES cells, digested with XbaI or SacI, electrophoresed and transferred to a positively charged nylon transfer membrane (Amersham Biosciences, Saclay, France). A 0.5 kb DNA fragment (NotI–NheI) located between exons 12 and 13, and a 0.5 kb DNA fragment (NotI SacII) placed between exons 19 and 20, were used as probes for MR. A 0.5 kb DNA fragment (NotI–NheI) located between exons 6 and 7 (39 probe) and a 0.5 kb DNA fragment (NotI–SacII) placed between exons 2 and 3 (59 probe) were used as probes for Dectin-1. The karyotype was verified and several correctly targeted ES cell clones were injected into blastocysts from C57BL/6J mice. These blastocysts were transferred into pseudo-pregnant females, resulting in chimeric offspring that were eventually mated with female C57BL/6J mice, which express the Flp recombinase under the control of the ubiquitous CMV promoter. The offspring that transmitted the mutated allele (in which the selection marker was excised) and that had lost the Flp transgene (MR<sup>+/L2</sup> mice) were then selected and used for systematic backcrossing with C57BL/6J mice to generate congenic MR floxed mouse lines or Dectin-1 floxed mice. A PCR genotyping strategy was subsequently used to identify MR<sup>+/+</sup>, <sup>+/L2</sup>, and L2/L2 mice. To generate myeloid-specific mutant (LysM-MR L2/L2) mice, MR L2/L2 mice were mated with LysM-Cre C57BL/6J mice in which the Cre recombinase was expressed under the control of the phagocyte-selective lysozyme promoter (Clausen et al., 1999) LysM-Cre/MR L2/+ mice, heterozygous for the floxed *Mrc1* allele, were selected and subsequently inter-crossed to generate pre-mutant LysM-Cre/MR L2/L2 mice (MR<sup>-/-</sup>). At least two more rounds of breeding were

required to generate age- and sex-matched mice for the experimental cohorts. The same strategy was used to generate LysM-Cre/Dectin-1 L2/L2 mice (Dectin-1<sup>-/-</sup>).

mRNA and protein expression of Dectin-1 and MR revealed that these CLR are expressed in myeloid lineage (macrophages, eosinophils, neutrophils) and epithelial cells but not in B and T immune cells (Figure S1A-D). The disruption of Dectin-1 and MR is only detected in myeloid lineage but not in other CLR-expressing cells, such as colonic epithelial cells (Figure S1A-D).

Dectin-1<sup>-/-</sup>, MR<sup>-/-</sup> and Dectin-1<sup>-/-</sup> MR<sup>-/-</sup> mice and their WT littermates are recombinant inbreeding populations. The random fixation and selection during the inbreeding process can explain the variability of some parameters observed between mouse models (Ashbrook et al., 2019).

*Alox5<sup>-/-</sup>*, *Alox15<sup>-/-</sup>* mice and C57BL/6 mice (corresponding controls) were purchased from The Jackson Laboratory (USA).

### **Dextran Sulfate Sodium (DSS) and 2,4,6-trinitrobenzenesulfonic acid (TNBS) models**

From day 1 to day 6, mice were given 1.5% DSS (MW 36.000-50.000, MP Biomedicals, France) through drinking water to induce intestinal inflammation. The health status of animals was monitored once daily during 8 days. After treatment, the mice were euthanized by CO<sub>2</sub>, and their colons were collected for further analyses.

For induction of TNBS colitis, anesthetized mice were given an intrarectal injection of a 150 mg/kg TNBS solution (Sigma, France) dissolved in 0.9% NaCl and mixed with an equal volume of ethanol. Control mice received 50% ethanol intrarectally. Animals were killed by CO<sub>2</sub> asphyxiation 24h after TNBS administration. Body weight and rectal bleeding were monitored during the experiment. Mice were killed, colons were measured and weighed, and macroscopic features were scored. All mice treated with DSS or TNBS develop colitis.

### ***In vivo* macrophage depletion protocol**

Mice received intraperitoneal injections of 5µg/kg of clodronate encapsulated liposomes or liposome for control (Clinisciences, France) one day before DSS treatment and 3 days after.



### ***In vivo* tracking of macrophages origin**

Ly5.1 mice (CD45.1 expressing B6.SJL-*Ptprc<sup>a</sup>Pepc<sup>b</sup>*/BoyCrl congenic) from Charles River received DSS for 4 days before injection into the ophthalmic venous sinus with sorted monocytes isolated from CD45.2 donor mice. Monocytes were isolated from bone marrow of Dectin-1<sup>-/-</sup> or MR<sup>-/-</sup> mice and their WT littermates according to Monocytes isolation kit recommendation's (Miltenyi, France). After 2 days of DSS treatment following by 2 days with drinking water, Ly5.1 mice were sacrificed. Cells were isolated by enzymatic digestion of colons (see below). Viable cells were analyzed by flow cytometry and the percent of macrophages (CD45.2<sup>+</sup>, CD11b<sup>+</sup>, F4/80<sup>+</sup>) were determined. CD45.2 cells from colons were sorted using CD45.2-FITC antibody and anti-FITC microbeads according to Miltenyi's protocol and the mRNA expression profile of pro and anti-inflammatory markers were evaluated using qRT-PCR.

### **Human subjects**

The part of the study involving human subjects was sponsored by the University Hospital of Toulouse for regulated and ethical submission (Clinical trials.gov NCT01990716). Colonic tissue samples were obtained from well-characterized CD and UC subjects undergoing colonoscopy or colonic resection procedures at the Toulouse Hospital Centre (France). Freshly isolated colonic biopsies from 9 healthy patients (5 females and 4 males; mean age 59, range 21-87 years), from 11 CD patients (5 females and 6 males; mean age 39, range 20-58 years) and from 9 UC patients (3 females and 6 males; mean age 49, range 34-67 years) were quick-frozen at -80°C until use for RNA extraction and gene expression analysis. Finally, 20 IBD patients (8 females and 12 males; mean age 42, range 20-67 years) were included in Figure 7A and S6A. For cytokines (IL1 $\beta$ , TNF $\alpha$ ), chemokines (CCL2) and LTB4 quantification by ELISA and EIA (Figure 7C and S6B), colonic biopsies or resection from 4 healthy patients (3 females and 1 males; mean age 68, range 68-69 years) and from 12 IBD patients (6 females and 6 males; mean age 45, range 16-73 years). Colonic tissue samples from 7 healthy patients (5 females and 2 males; mean age 62, range 43-69 years)

and from 20 IBD patients (9 females and 12 males; mean age 40, range 16-73 years) were digested to isolate the cells and flow cytometry analysis.

### **Isolation of mice and human colonic macrophages**

This protocol was developed and modified as described previously (Weigmann B, Tubbe I, Seidel D, Nicolaev A, Becker C, Neurath MF., 2007). Excised mouse colons or colonic mucosae from healthy or IBD subjects undergoing colectomy sections from surgery were washed with cold PBS 1% BSA and cut longitudinally into approximately 1cm lengths. The pieces were incubated twice in RPMI 5% FCS, 0.2 mM EDTA for 20 min at 37°C with slow, regular shaking. The pieces were passed through a 100µm nylon membrane after each incubation. The flow-through contains colonic content with epithelial cells and intra-epithelial lymphocytes. The pieces were then digested 3 times for 20 min at 37°C with collagenase D (0.2 mg/ml, Sigma, France), dispase-II (3 mg/ml, Roche, Mannheim, Germany), Dnase-I (0.2 mg/ml, Roche) in RPMI 10% FCS with slow, regular shaking. Cells were collected by centrifugation and subjected to a gradient of Percoll® (gradient 30%/40%/70%; Sigma, France).

### **Isolation of blood monocytes**

Monocytes were isolated from blood using a Ficoll gradient (Abcys).

### **Macrophage culture**

Resident murine peritoneal cells were harvested from Dectin-1<sup>-/-</sup> and MR<sup>-/-</sup> mice and their respective wild-type (WT) littermates. The cells were primed with lipopolysaccharide (LPS, 10 ng/ml; Sigma, France) overnight before treatment with mannan (from *S. cerevisiae*, 1.25 mg/ml; Sigma, France), zymosan (10 µg/ml, Sigma, France) and with or without 5% DSS, caspase-1 inhibitor (Z-YVAD, 50 µM; Calbiochem) or LTB<sub>4</sub> (10<sup>-7</sup> M; Cayman) for 7 h. Culture supernatants were used for enzyme-linked immunosorbent assay (ELISA), Enzyme Immunoassay (EIA) or immunoblotting. The cells were used for immunoblotting.

## **METHOD DETAILS**

### **Myeloperoxidase activity (MPO)**

MPO activity in colon tissue was measured *via* chemiluminescence in the presence of 5-amino-2,3-dihydro-1,4-phthalazinedione (100  $\mu$ M) and hydrogen peroxide (0.1 M) using a luminometer (EnVision, PerkinElmer). Statistical analysis was performed using the area under the curve expressed in counts  $\times$  second.

### **Macroscopic scoring and histological analysis**

Macroscopic scores of colons were determined according to the criteria defined earlier (Kimball et al., 2004). One part of the distal colon was fixed overnight in 4% paraformaldehyde and embedded in paraffin; sections of mouse colon were stained with hematoxylin and eosin (H&E) and scored according to the Ameho criteria (Ameho et al., 1997).

### **Reverse transcription and qPCR**

mRNA from colonic macrophages or from human biopsies were prepared and cDNA were synthesized according to the manufacturer's recommendations (Total RNA Minipreps super kit, BioBasic; Verso cDNA kit, Thermo Fisher Scientific). qRT-PCR was performed on a LightCycler 480 system with LightCycler SYBR Green I Master (Roche Diagnostics, France). Serially diluted samples of pooled cDNA were used as external standards in each run for the quantification and results were expressed in fold induction relative to the respective control. The primers are listed in Supplementary Tables 1 and 2. GAPDH,  $\beta$ -actin or 18S mRNA were used as housekeeping genes.

### **Flow Cytometry**

To distinguish viable cells, cells were incubated with Live/Dead® Fixable Violet dead cell stain kits (Lifetechnology, Oregon, USA) before antibodies. The murine cells were labeled with the following antibodies: anti-CD45, anti-CD45.1, anti-CD45.2, anti-F4/80, anti-SiglecF, anti-Ly6G, anti-Dectin-1,

anti-Cd209b (SIGN-R1), anti-CD11b, anti-Ly6C, anti-CD43, anti-CCR2, anti-CD326 (EpCAM) (Miltenyi, France), and anti-MR (CD206) (Ozyme, France). Epithelial cells were identified as EpCAM<sup>+</sup> cells. Macrophages were identified as CD45<sup>+</sup>, CD11b<sup>+</sup>, F4/80<sup>+</sup>, SiglecF<sup>-</sup>, Ly6G<sup>-</sup> cells. Eosinophils were identified as CD45<sup>+</sup>, F4/80<sup>+</sup>, CD11b<sup>+</sup>, SiglecF<sup>+</sup>, Ly6G<sup>-</sup> cells. Neutrophils were identified as CD45<sup>+</sup>, F4/80<sup>-</sup>, CD11b<sup>+</sup>, Ly6G<sup>+</sup>, SiglecF<sup>-</sup> cells. Monocytes were identified as CD11b<sup>+</sup>, CD45<sup>+</sup>, Ly6C<sup>+</sup>, CD43<sup>+</sup>, CCR2<sup>-/+</sup> cells.

The human cells were labeled with the following antibodies: anti-CD64 (Serotec, France), anti-CD206 (BD Pharmingen), anti-Dectin-1 (Miltenyi, France).

Flow cytometry was performed using a BD LSR Fortessa (BD Biosciences). Flow cytometry data were analyzed with FACS Diva software (BD Biosciences).

### **Immunoblot analysis**

Total protein was extracted from cell lysates using an RIPA buffer. Proteins from the culture supernatant were concentrated using trichloroacetic acid precipitation. Rabbit polyclonal anti-caspase-1 p10 antibody or goat anti- $\beta$ -actin (C11) antibody (Santa Cruz Biotechnology, USA) was used.

### **ELISA, enzyme immunoassay lipid quantification (EIA) and AA mobilization assay**

Cytokines and chemokine were quantified with ELISA kits for IL1 $\beta$ , TNF $\alpha$ , IL6 and CCL2 (BD Biosciences, R&D Systems). LTB4 levels were evaluated with an EIA kit (Oxford). The kits were used according to the manufacturer's instructions. The AA mobilization assay was performed as described previously (Lefèvre et al., 2013).

### **DNA isolation and analysis of fungal and bacteria colonization**

DNA was purified using High Pure PCR Template preparation kits (Roche, Mannheim, Germany). For evaluation of mucosae-associated fungal or bacteria colonization, semi-quantitative PCR was performed on DNA isolated from intestinal mucosae using primers listed in Supplementary Table 3. Relative quantity was calculated and normalized to the amount of  $\beta$ -actin. For amplicon detection,

the LightCycler FastStart DNA SYBR Green I kit was used as described by the manufacturer (Roche).

## QUANTIFICATION AND STATISTICAL ANALYSIS

Data are expressed as mean  $\pm$  SEM. For each experiment, the data was subjected to one-way analysis of variance followed by multiple comparisons of means using the Bonferroni-Dunnnett method. P-value<0.05 was defined as the level of statistical significance.

## DATA AND CODE AVAILABILITY

This study did not generate/analyze datasets/code.

## REFERENCES

- Amaral, F.A., Costa, V.V., Tavares, L.D., Sachs, D., Coelho, F.M., Fagundes, C.T., Soriani, F.M., Silveira, T.N., Cunha, L.D., Zamboni, D.S., et al. (2012). NLRP3 inflammasome-mediated neutrophil recruitment and hypernociception depend on leukotriene B4 in a murine model of gout. *Arthritis Rheum.* *64*, 474–484.
- Ashbrook, D.G., Arends, D., Prins, P., Mulligan, M.K., Roy, S., Williams, E.G., Lutz, C.M., Valenzuela, A., Bohl, C.J., Ingels, J.F., et al. (2019). The expanded BXD family of mice: A cohort for experimental systems genetics and precision medicine. *bioRxiv* 672097.
- Bain, C.C., and Mowat, A.M. (2014). The monocyte-macrophage axis in the intestine. *Cell. Immunol.* *291*, 41–48.
- Bauer, C., Duewell, P., Mayer, C., Lehr, H.A., Fitzgerald, K.A., Dauer, M., Tschopp, J., Endres, S., Latz, E., and Schnurr, M. (2010). Colitis induced in mice with dextran sulfate sodium (DSS) is mediated by the NLRP3 inflammasome. *Gut* *59*, 1192–1199.
- Bersudsky, M., Luski, L., Fishman, D., White, R.M., Ziv-Sokolovskaya, N., Dotan, S., Rider, P., Kaplanov, I., Aychek, T., Dinarello, C.A., et al. (2014). Non-redundant properties of IL-1 and IL-1 during acute colon inflammation in mice. *Gut* *63*, 598–609.
- Cheng, S.-C., van de Veerdonk, F.L., Lenardon, M., Stoffels, M., Plantinga, T., Smeekens, S., Rizzetto, L., Mukaremera, L., Preechasuth, K., Cavalieri, D., et al. (2011). The dectin-1/inflammasome pathway is responsible for the induction of protective T-helper 17 responses that discriminate between yeasts and hyphae of *Candida albicans*. *J. Leukoc. Biol.* *90*, 357–366.
- Chieppa, M., Bianchi, G., Doni, A., Del Prete, A., Sironi, M., Laskarin, G., Monti, P., Piemonti, L., Biondi, A., Mantovani, A., et al. (2003). Cross-Linking of the Mannose Receptor on Monocyte-Derived Dendritic Cells Activates an Anti-Inflammatory Immunosuppressive Program. *J. Immunol.* *171*, 4552–4560.

- Clausen, B.E., Burkhardt, C., Reith, W., Renkawitz, R., and Förster, I. (1999). Conditional gene targeting in macrophages and granulocytes using LysMcre mice. *Transgenic Res.* *8*, 265–277.
- Coste, A., Dubourdeau, M., Linas, M.D., Cassaing, S., Lepert, J.-C., Balard, P., Chalmeton, S., Bernad, J., Orfila, C., Séguéla, J.-P., et al. (2003). PPAR $\gamma$  promotes mannose receptor gene expression in murine macrophages and contributes to the induction of this receptor by IL-13. *Immunity* *19*, 329–339.
- Dupaul-Chicoine, J., Yeretssian, G., Doiron, K., Bergstrom, K.S.B., McIntire, C.R., LeBlanc, P.M., Meunier, C., Turbide, C., Gros, P., Beauchemin, N., et al. (2010). Control of intestinal homeostasis, colitis, and colitis-associated colorectal cancer by the inflammatory caspases. *Immunity* *32*, 367–378.
- Galès, A., Conduché, A., Bernad, J., Lefevre, L., Olagnier, D., Béraud, M., Martin-Blondel, G., Linas, M.-D., Auwerx, J., Coste, A., et al. (2010). PPAR $\gamma$  Controls Dectin-1 Expression Required for Host Antifungal Defense against *Candida albicans*. *PLoS Pathog.* *6*, e1000714.
- Grainger, J.R., Konkel, J.E., Zangerle-Murray, T., and Shaw, T.N. (2017). Macrophages in gastrointestinal homeostasis and inflammation. *Pflug. Arch. - Eur. J. Physiol.* *469*, 527–539.
- Heinsbroek, S.E., Oei, A., Roelofs, J.J., Dhawan, S., te Velde, A., Gordon, S., and de Jonge, W.J. (2012). Genetic deletion of dectin-1 does not affect the course of murine experimental colitis. *BMC Gastroenterol.* *12*, 33.
- Heinsbroek, S.E.M., Williams, D.L., Welting, O., Meijer, S.L., Gordon, S., and de Jonge, W.J. (2015). Orally delivered  $\beta$ -glucans aggravate dextran sulfate sodium (DSS)-induced intestinal inflammation. *Nutr. Res.* *35*, 1106–1112.
- Heinsbroek, S.E.M., Squadrito, M.L., Schilderink, R., Hilbers, F.W., Verseijden, C., Hofmann, M., Helmke, A., Boon, L., Wildenberg, M.E., Roelofs, J.J.T.H., et al. (2016). miR-511-3p, embedded in the macrophage mannose receptor gene, contributes to intestinal inflammation. *Mucosal Immunol.* *9*, 960–973.
- Hunter, M.M., Wang, A., Parhar, K.S., Johnston, M.J.G., Van Rooijen, N., Beck, P.L., and McKay, D.M. (2010). In Vitro-Derived Alternatively Activated Macrophages Reduce Colonic Inflammation in Mice. *Gastroenterology* *138*, 1395–1405.
- Iliev, I.D., and Leonardi, I. (2017). Fungal dysbiosis: immunity and interactions at mucosal barriers. *Nat. Rev. Immunol.* *17*, 635–646.
- Iliev, I.D., Funari, V.A., Taylor, K.D., Nguyen, Q., Reyes, C.N., Strom, S.P., Brown, J., Becker, C.A., Fleshner, P.R., Dubinsky, M., et al. (2012). Interactions Between Commensal Fungi and the C-Type Lectin Receptor Dectin-1 Influence Colitis. *Science* *336*, 1314–1317.
- Jupp, J., Hillier, K., Elliott, D.H., Fine, D.R., Bateman, A.C., Johnson, P.A., Cazaly, A.M., Penrose, J.F., and Sampson, A.P. (2007). Colonic expression of leukotriene-pathway enzymes in inflammatory bowel diseases: *Inflamm. Bowel Dis.* *13*, 537–546.
- Kimball, E.S., Wallace, N.H., Schneider, C.R., D'Andrea, M.R., and Hornby, P.J. (2004). Vanilloid receptor 1 antagonists attenuate disease severity in dextran sulphate sodium-induced colitis in mice. *Neurogastroenterol. Motil.* *16*, 811–818.
- Kühl, A.A., Erben, U., Kredel, L.I., and Siegmund, B. (2015). Diversity of Intestinal Macrophages in Inflammatory Bowel Diseases. *Front. Immunol.* *6*.

- Lefèvre, L., Lugo-Villarino, G., Meunier, E., Valentin, A., Olagnier, D., Authier, H., Duval, C., Dardenne, C., Bernad, J., Lemesre, J.L., et al. (2013). The C-type Lectin Receptors Dectin-1, MR, and SIGNR3 Contribute Both Positively and Negatively to the Macrophage Response to *Leishmania infantum*. *Immunity* *38*, 1038–1049.
- Leonardi, I., Li, X., Semon, A., Li, D., Doron, I., Putzel, G., Bar, A., Prieto, D., Rescigno, M., and McGovern, D.P. (2018). CX3CR1<sup>+</sup> mononuclear phagocytes control immunity to intestinal fungi. *Science* *359*, 232–236.
- Lin, Y., Yang, X., Yue, W., Xu, X., Li, B., Zou, L., and He, R. (2014). Chemerin aggravates DSS-induced colitis by suppressing M2 macrophage polarization. *Cell. Mol. Immunol.* *11*, 355–366.
- Lissner, D., Schumann, M., Batra, A., Kredel, L.-I., Kühl, A.A., Erben, U., May, C., Schulzke, J.-D., and Siegmund, B. (2015). Monocyte and M1 Macrophage-induced Barrier Defect Contributes to Chronic Intestinal Inflammation in IBD: *Inflamm. Bowel Dis.* *1*.
- Liu, L., Guo, Z., Lv, Z., Sun, Y., Cao, W., Zhang, R., Liu, Z., Li, C., Cao, S., and Mei, Q. (2008). The beneficial effect of *Rheum tanguticum* polysaccharide on protecting against diarrhea, colonic inflammation and ulceration in rats with TNBS-induced colitis: The role of macrophage mannose receptor in inflammation and immune response. *Int. Immunopharmacol.* *8*, 1481–1492.
- Loures, F.V., Araujo, E.F., Feriotti, C., Bazan, S.B., Costa, T.A., Brown, G.D., and Calich, V.L.G. (2014). Dectin-1 Induces M1 Macrophages and Prominent Expansion of CD8<sup>+</sup>IL-17<sup>+</sup> Cells in Pulmonary Paracoccidioidomycosis. *J. Infect. Dis.* *210*, 762–773.
- Mao, L., Kitani, A., Strober, W., and Fuss, I.J. (2018). The Role of NLRP3 and IL-1 $\beta$  in the Pathogenesis of Inflammatory Bowel Disease. *Front. Immunol.* *9*.
- McAlindon, M.E., Hawkey, C.J., and Mahida, Y.R. (1998). Expression of interleukin 1 $\beta$  and interleukin 1 $\beta$  converting enzyme by intestinal macrophages in health and inflammatory bowel disease. *Gut* *42*, 214–219.
- Neurath, M.F. (2014). Cytokines in inflammatory bowel disease. *Nat. Rev. Immunol.* *14*, 329–342.
- Ohkusa, T., and Koido, S. (2015). Intestinal microbiota and ulcerative colitis. *J. Infect. Chemother.* *21*, 761–768.
- Pelegri, P., and Surprenant, A. (2009). Dynamics of macrophage polarization reveal new mechanism to inhibit IL-1 $\beta$  release through pyrophosphates. *EMBO J.* *28*, 2114–2127.
- Saunders, S.P., Barlow, J.L., Walsh, C.M., Bellsoi, A., Smith, P., McKenzie, A.N.J., and Fallon, P.G. (2010). C-Type Lectin SIGN-R1 Has a Role in Experimental Colitis and Responsiveness to Lipopolysaccharide. *J. Immunol.* *184*, 2627–2637.
- Sokol, H., Leducq, V., Aschard, H., Pham, H.-P., Jegou, S., Landman, C., Cohen, D., Liguori, G., Bourrier, A., Nion-Larmurier, I., et al. (2016). Fungal microbiota dysbiosis in IBD. *Gut gutjnl* – 2015–310746.
- Suram, S., Brown, G.D., Ghosh, M., Gordon, S., Loper, R., Taylor, P.R., Akira, S., Uematsu, S., Williams, D.L., and Leslie, C.C. (2006). Regulation of Cytosolic Phospholipase A2 Activation and Cyclooxygenase 2 Expression in Macrophages by the  $\beta$ -Glucan Receptor. *J. Biol. Chem.* *281*, 5506–5514.
- Tang, C., Kamiya, T., Liu, Y., Kadoki, M., Kakuta, S., Oshima, K., Hattori, M., Takeshita, K., Kanai, T., Saijo, S., et al. (2015). Inhibition of Dectin-1 Signaling Ameliorates Colitis by Inducing

Lactobacillus-Mediated Regulatory T Cell Expansion in the Intestine. *Cell Host Microbe* 18, 183–197.

Van de Veerdonk, F.L., Joosten, L.A.B., Devesa, I., Mora-Montes, H.M., Kanneganti, T., Dinarello, C.A., van der Meer, J.W.M., Gow, N.A.R., Kullberg, B.J., and Netea, M.G. (2009). Bypassing Pathogen-Induced Inflammasome Activation for the Regulation of Interleukin-1 $\beta$  Production by the Fungal Pathogen *Candida albicans*. *J. Infect. Dis.* 199, 1087–1096.

Vos, A.C.W., Wildenberg, M.E., Arijs, I., Duijvestein, M., Verhaar, A.P., de Hertogh, G., Vermeire, S., Rutgeerts, P., van den Brink, G.R., and Hommes, D.W. (2012). Regulatory macrophages induced by infliximab are involved in healing in vivo and in vitro: *Inflamm. Bowel Dis.* 18, 401–408.

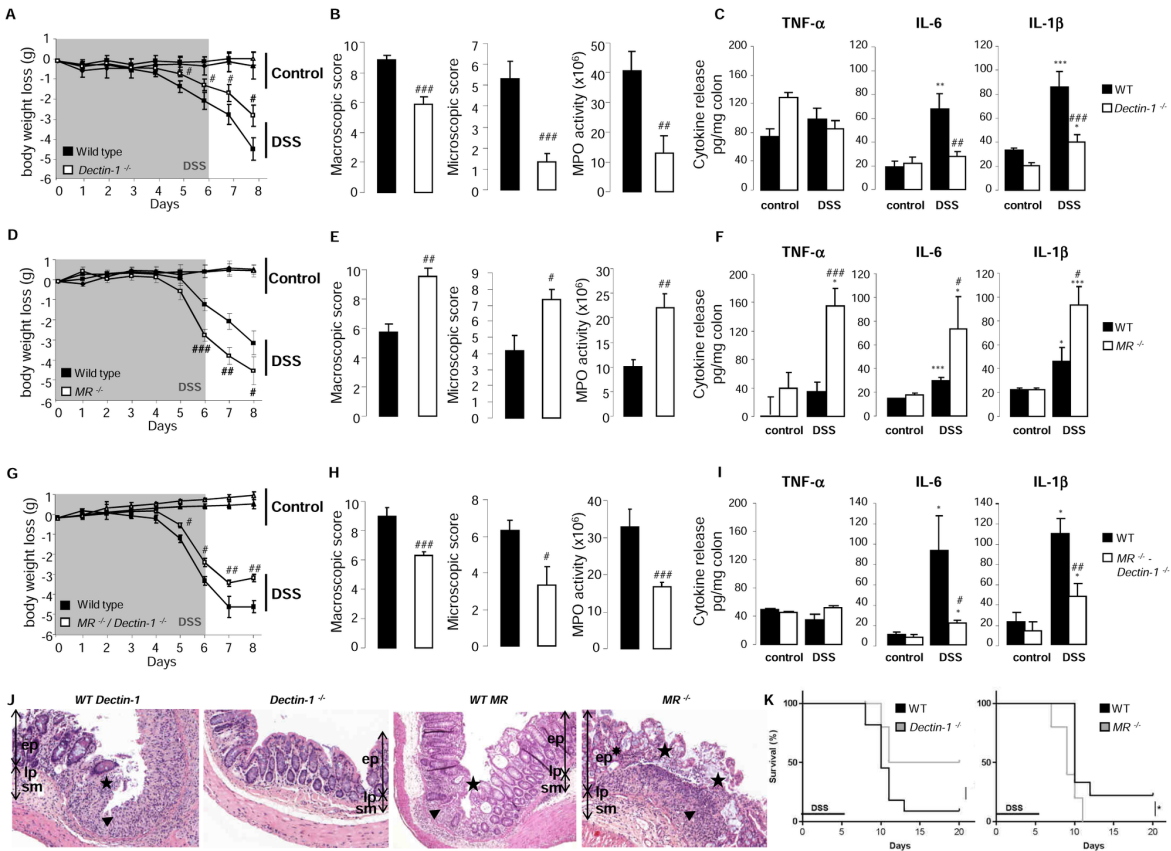
De Vries, H.S., Plantinga, T.S., van Krieken, J.H., Stienstra, R., van Bodegraven, A.A., Festen, E.A.M., Weersma, R.K., Crusius, J.B.A., Linskens, R.K., Joosten, L.A.B., et al. (2009). Genetic Association Analysis of the Functional c.714T>G Polymorphism and Mucosal Expression of Dectin-1 in Inflammatory Bowel Disease. *PLoS ONE* 4, e7818.

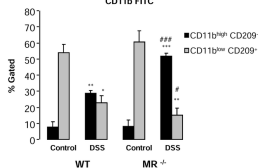
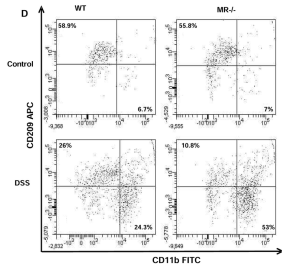
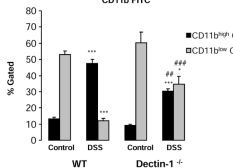
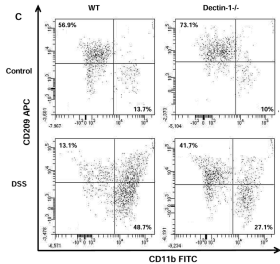
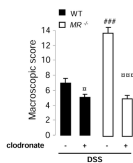
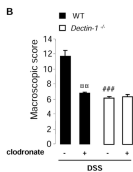
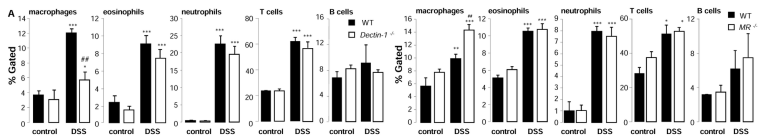
Weigmann B, Tubbe I, Seidel D, Nicolaev A, Becker C, Neurath MF. (2007). Isolation and subsequent analysis of murine lamina propria mononuclear cells from colonic tissue. *Nat Protoc* 2(10):2307–2311.

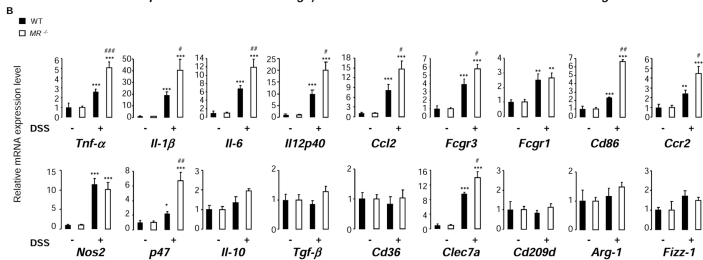
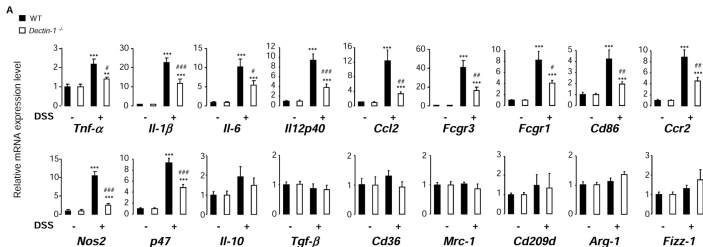
Yang, J., Zhang, L., Yu, C., Yang, X.-F., and Wang, H. (2014). Monocyte and macrophage differentiation: circulation inflammatory monocyte as biomarker for inflammatory diseases. *Biomark. Res.* 2, 1.

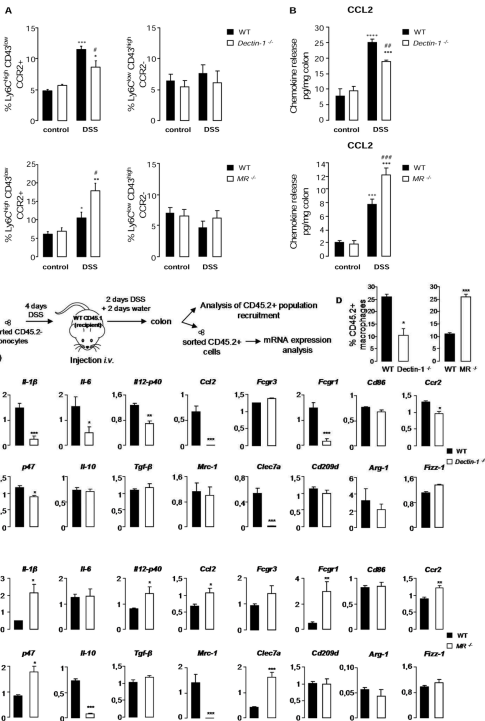
Zigmond, E., Varol, C., Farache, J., Elmaliyah, E., Satpathy, A.T., Friedlander, G., Mack, M., Shpigel, N., Boneca, I.G., Murphy, K.M., et al. (2012). Ly6Chi Monocytes in the Inflamed Colon Give Rise to Proinflammatory Effector Cells and Migratory Antigen-Presenting Cells. *Immunity* 37, 1076–1090.



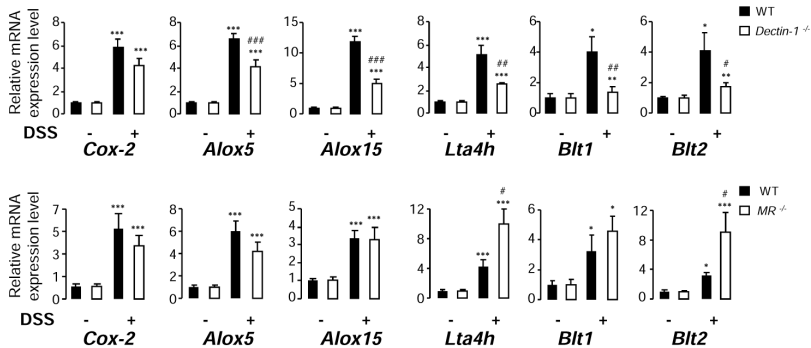




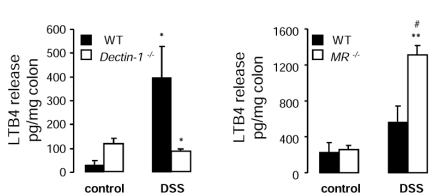




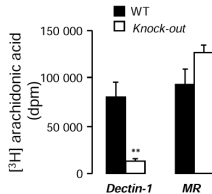
A

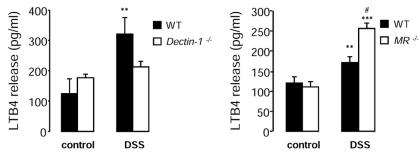
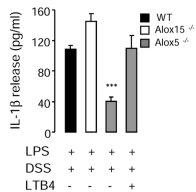
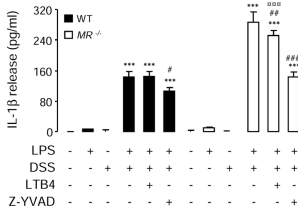
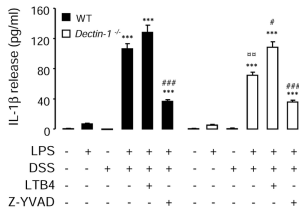


B



C



**A****B****C****D**