The role of dendritic cells during infection with the gastrointestinal parasite Trichuris muris

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2017

Document Version:
Publisher’s PDF, also known as Version of record

Link to publication

Citation for published version (APA):
Demiri, M. (2017). The role of dendritic cells during infection with the gastrointestinal parasite Trichuris muris
Lund : Lund University, Faculty of Medicine

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The role of dendritic cells during infection with the gastrointestinal parasite *Trichuris muris*

Mimoza Demiri

LUND UNIVERSITY

DOCTORAL DISSERTATION
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To be defended on Friday 24\textsuperscript{th} of November, 9.00 in Belfragesalen, BMC D15,
Sölvegatan 19, Lund

*Faculty opponent*
Associate Professor Susanne Nylén
Abstract

Adaptive immune responses are critical for mediating sterilizing immunity and induce immunological memory during infection. Conventional dendritic cells (cDC) play a critical role in the induction of adaptive T cell responses, by acquiring and transporting antigens from tissues to local draining lymph nodes, where they are presented in order to activate and polarize T cells. The nature of the effector T helper (Th) cell response is dictated by signals from the cDC, and recent work has established that distinct cDC subsets can promote different Th cell responses. Adaptive Th2 responses promote immunity to helminth infections, while Th1 responses are associated with chronic infections; however, the role of cDC subsets in the generation of these responses is not fully understood. The aim of this thesis has been to determine the contribution of cDC subsets in the generation of adaptive immune responses to acute and chronic infection with the gastrointestinal nematode *Trichuris muris*.

In the first paper, we examined the role of IRF8-dependent cDC in intestinal homeostasis, by studying mice that are deficient in IRF8 specifically in CD11c-expressing cells, resulting in the absence of IRF8-dependent cDCs. Our results demonstrated a role of IRF8-dependent cDCs in the generation of Th1 responses in the intestinal mucosa. Consistent with this, mice lacking IRF8-dependent cDCs failed to become chronically infected following a Th1-associated low dose-infection with *T. muris*.

In the second paper, we assessed the role of IRF4-dependent cDCs in the generation of colonic and small intestinal Th2 responses, in two complementary models: live infection with *T. muris*, and subserosal injection of Th2-promoting *Schistosoma* egg antigens (SEA). In both models, we could demonstrate that IRF4-dependent cDCs are critical for induction of Th2 responses. In addition, we showed a regionally compartmentalized role of cDCs in this process, such that while CD11b+ CD103+ cDCs were the Th2-inducing subset after antigen delivery in the small intestine, CD11b+ CD103- cDCs performed this task in the colon.

In the third paper, we further investigated the role of IRF4 and IRF8-dependent cDC during induction of adaptive Th1 and Th2 responses. Here, we extended out previous analysis by demonstrating that absence of IRF8-dependent cDCs and failure to support chronic infection indeed was associated with a failure to induce Th1 cells. Interestingly, this was associated with a strong increase in the production of Th2 cytokines, indicating that IRF8-dependent cDCs may act to antagonize Th2 responses. Furthermore, by generating bone marrow chimeric IRF4- and IRF8-double deficient mice, we could demonstrate that Th2 responses can be induced in the absence of IRF4-dependent cDCs, in the concurrent absence of IRF8-dependent cDCs.

Taken together, our work demonstrates that adaptive immune responses to Th2-associated, acute and Th1-associated, chronic infection with *T. muris* is mediated by IRF4- and IRF8-dependent cDC, respectively. In addition, our work highlights a potential antagonistic capacity of these cDC subsets in regulation of the induction of adaptive immune responses. Finally, we demonstrate that although IRF4-dependent cDCs are critical for induction of Th2 responses under normal conditions, this can be accomplished by additional antigen-presenting cells in the combined absence of IRF4- and IRF8-dependent cDCs. This work contributes to the understanding of how adaptive immune responses in the intestinal mucosa are controlled; however, further work will be required to unravel the underlying molecular mechanism controlling this capacity.

Key words: *T. muris*, Dendritic cells, T cells, Th1 and Th2, Intestinal helminth infection
The role of dendritic cells during infection with the gastrointestinal parasite *Trichuris muris*

Mimoza Demiri

Section for Immunology
Department of Experimental Medical Science
Faculty of Medicine
Për mamin dhe babin
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Paper I

**IRF8 Transcription-Factor-Dependent Classical Dendritic Cells Are Essential for Intestinal T Cell Homeostasis.**


*Immunity.* 2016 Apr 19;44(4):860-74*

Paper II

**Different populations of CD11b+ dendritic cells drive Th2 responses in the small intestine and colon.**


*Nature Communication* 2017 Jun 9;8:15820*

Paper III

**Distinct DC subsets regulate adaptive Th1 and 2 responses during Trichuris muris infection.**

Mimoza Demiri, Katarzyna Müller-Luda, William W. Agace, Marcus Svensson-Frej

*Parasite Immunology* 2017 Oct;39(10)*

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### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>APC</td>
<td>Antigen presenting cell</td>
</tr>
<tr>
<td>Batf3</td>
<td>Basic Leucine Zipper ATF-Like Transcription Factor 3</td>
</tr>
<tr>
<td>BM</td>
<td>Bone marrow</td>
</tr>
<tr>
<td>CCR</td>
<td>C-C chemokine receptor</td>
</tr>
<tr>
<td>CD</td>
<td>Cluster of differentiation</td>
</tr>
<tr>
<td>cDC</td>
<td>Conventional dendritic cell</td>
</tr>
<tr>
<td>CDP</td>
<td>Common dendritic cell progenitor</td>
</tr>
<tr>
<td>CLR</td>
<td>C-type lectin receptor</td>
</tr>
<tr>
<td>CX3CR1</td>
<td>Chemokine (C-X3-C motif) receptor 1</td>
</tr>
<tr>
<td>DAMP</td>
<td>Damage-associated molecular patterns</td>
</tr>
<tr>
<td>DC</td>
<td>Dendritic cell</td>
</tr>
<tr>
<td>DNGR-1</td>
<td>DC NK lectin group receptor-1</td>
</tr>
<tr>
<td>E/S</td>
<td>Excretory/Secretory</td>
</tr>
<tr>
<td>GALT</td>
<td>Gut associated lymphoid tissue</td>
</tr>
<tr>
<td>GM-CSF</td>
<td>Granulocyte-macrophage colony-stimulating factor</td>
</tr>
<tr>
<td>Id2</td>
<td>Inhibitor of dna binding 2</td>
</tr>
<tr>
<td>IEC</td>
<td>Intestinal epithelial cell</td>
</tr>
<tr>
<td>IEL</td>
<td>Intraepithelial lymphocyte</td>
</tr>
<tr>
<td>IFN</td>
<td>Interferon</td>
</tr>
<tr>
<td>Ig</td>
<td>Immunoglobulin</td>
</tr>
<tr>
<td>IL</td>
<td>Interleukin</td>
</tr>
<tr>
<td>ILC</td>
<td>Innate lymphoid cells</td>
</tr>
<tr>
<td>ILF</td>
<td>Isolated lymphoid follicle</td>
</tr>
<tr>
<td>IRF</td>
<td>Interferon regulatory factor</td>
</tr>
<tr>
<td>KO</td>
<td>Knock-out</td>
</tr>
<tr>
<td>LI</td>
<td>Large intestine</td>
</tr>
<tr>
<td>LN</td>
<td>Lymph node</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>LP</td>
<td>Lamina propria</td>
</tr>
<tr>
<td>MDP</td>
<td>Monocyte-macrophage dendritic cell progenitor</td>
</tr>
<tr>
<td>MHC</td>
<td>Major histocompatibility complex</td>
</tr>
<tr>
<td>MLN</td>
<td>Mesenteric lymph node</td>
</tr>
<tr>
<td>NF-κβ</td>
<td>Nuclear factor kappa-light-chain-enhancer of activated B cells</td>
</tr>
<tr>
<td>NLR</td>
<td>Nod like receptor</td>
</tr>
<tr>
<td>OVA</td>
<td>Ovalbumin</td>
</tr>
<tr>
<td>PAMP</td>
<td>Pathogen associated molecular pattern</td>
</tr>
<tr>
<td>PRR</td>
<td>Pathogen recognition receptor</td>
</tr>
<tr>
<td>RA</td>
<td>Retinoic acid</td>
</tr>
<tr>
<td>RALDH2</td>
<td>Retinaldehyde dehydrogenase 2</td>
</tr>
<tr>
<td>RLR</td>
<td>RIG-I-like receptor</td>
</tr>
<tr>
<td>SI</td>
<td>Small intestine</td>
</tr>
<tr>
<td>SIRPα</td>
<td>Signal regulatory protein α</td>
</tr>
<tr>
<td>STAT</td>
<td>Signal transducer and activator of transcription</td>
</tr>
<tr>
<td>TCR</td>
<td>T cell receptor</td>
</tr>
<tr>
<td>TED</td>
<td>Transepithelial dendrites</td>
</tr>
<tr>
<td>TGF</td>
<td>Tumor growth factor</td>
</tr>
<tr>
<td>Th</td>
<td>T helper</td>
</tr>
<tr>
<td>TLR</td>
<td>Toll-like receptor</td>
</tr>
<tr>
<td>TNF</td>
<td>Tumor necrosis factor</td>
</tr>
<tr>
<td>TSLP</td>
<td>Thymic stromal lymphopoietin</td>
</tr>
<tr>
<td>WT</td>
<td>Wild type</td>
</tr>
<tr>
<td>XCR1</td>
<td>X-C motif chemokine receptor 1</td>
</tr>
<tr>
<td>Zbtb46</td>
<td>Zinc finger and BTB domain containing 46</td>
</tr>
</tbody>
</table>
1. The intestinal mucosa and immunity

1.1 The intestinal mucosa

The intestine is a tube-like organ spanning from the oral cavity to the rectum, and represent the body’s largest surface towards the environment. The intestine is divided into the small intestine, in which the majority of nutrient uptake occurs, and the large intestine, responsible for the absorption of water and excretion of waste products. In addition, the intestine is also housing a huge amount of commensal bacteria, in particular in the colon, which play important roles in immune development and function. Given the large surface area of the intestinal mucosa, together with the vast amount of food antigens and commensal and pathogenic microbes present in the intestinal lumen, it is not surprising that the intestinal mucosal contains the highest number of immune cells in the body. Because of this enormous exposure of the outside world, there is a high demand on a highly organized and tightly regulated intestinal mucosal immune defences, which can act by either dampening immune responses towards harmless substances, or respond effectively upon pathogen encounter.

The first line of defence in the intestinal immune system consists of non-cellular and cellular barriers, consisting of the mucous layer and a monolayer of epithelial cells that protects the underlying tissue, the lamina propria. The lamina propria is populated by a large variety of immune cells, such as dendritic cells (DC), macrophages, lymphocytes and innate lymphoid cells (ILC), serving to recognize and respond to potential pathogenic insult. To their help, many of these immune cells are equipped with pattern recognition receptors (PRR), germline-encoded receptors that recognize essential and conserved microbial molecules, so called pathogen-associated molecular pattern (PAMPs), e.g. bacterial cell-wall components or viral nucleic acids. PRR can be expressed in the membranes of the cell-surface or vesicles, e.g. toll-like receptors (TLR), or in the cytosol (e.g. NOD-like receptors and RIG-I-like receptors). In addition to microbial products, some PRR can also recognize endogenous molecules associated with tissue damage, damage-associated molecular patterns (DAMP), and so also respond to injury. Binding of ligands to PRR mediates induction of pro-inflammatory responses, e.g.
recruitment and activation of immune cells by production of chemokines and cytokines, which serve to eradicate the infectious agent. In addition, PRR signalling can also trigger migration of DCs from the tissue to local lymphoid inductive sites to induce an adaptive immune response.\textsuperscript{4}

1.2 The intestinal barrier

Pathogen entry into the intestinal mucosa is prevented by physiological as well as immunological mechanisms. The first physical barrier that needs to be breached by invading pathogens is the mucous layer, which protects the underlying epithelium from external damage.\textsuperscript{5-8} This mucous layer is made up of heavy O-glycosylated glycoproteins, which can either be attached to the epithelial surface via a transmembrane domain, or form a loose gel-like mucus.\textsuperscript{5,6} The intestinal epithelial layer itself serves as the second line of defence against the environment and protects the underlying lamina propria cells from direct contact with luminal contents. Epithelial cells are under constant replacement, and are exchanged every 4-5 days.\textsuperscript{9} The cell types making up the epithelial layer consists of several distinct types, including enterocytes, enteroendocrine cells, Paneth cells, tuft cells and goblet cells,\textsuperscript{10-13} all which are derived from Lgr5\textsuperscript{+} stem cells located in the basal crypts.\textsuperscript{14,15} In order to maintain a protective barrier, the integrity of the epithelial monolayer is further strengthened by various types of epithelial junction complexes which differ in their morphology and function,\textsuperscript{16} and prevent diffusion of proteins and lipids across the epithelial layer.\textsuperscript{17} Tight junctions, consisting of e.g. claudins and occludins, are critical for maintaining the barrier integrity, while permitting passage of small molecules.\textsuperscript{18} Epithelial integrity is essential for homeostasis, and disruption may lead to pathological conditions varying from minor outcomes such as epithelial cell death, to more severe effects that could advance into inflammatory bowel disease (IBD).\textsuperscript{19-29} In addition to being a physical barrier, and although not strictly belonging to the innate immune system, intestinal epithelial cells also have functions associated with immune cells. For example, epithelial cells have the ability to act as antigen-presenting cells (APC),\textsuperscript{30} and to directly produce and secrete antimicrobial mediators into the intestinal lumen.\textsuperscript{31} Furthermore, upon PRR activation, epithelial cells can release a variety of cytokines and chemokines;\textsuperscript{32} in this way, the epithelial cells can interact with and direct the function of immune cells in the underlying lamina propria. In addition, antigen-presenting cells in the intestinal lamina propria, including macrophages and DCs, can also take up and present antigens derived from dying epithelial cells.\textsuperscript{33,34}
1.3 Antigen recognition and uptake in the intestine

The intestinal lamina propria and epithelium are associated with several immune inductive sites, including the mesenteric lymph nodes (MLN), and gut-associated lymphoid tissues (GALT), consisting of Peyer’s patches (PP) and isolated lymphoid follicles (ILFs). Antigen uptake into the intestinal mucosa can occur by a variety of mechanisms and routes. One of the best characterised ways of antigen uptake occurs via so called microfold (M) cells, which are located in the follicle-associated epithelium (FAE), covering Payer’s patches and isolated lymphoid follicles. M cells differ in their microvillus structure as well as functionally compared to other epithelial cells, and have the ability to transfer antigens or pathogens to immune cells in the underlying lymphoid structure, and even present endocytosed antigens to neighbouring cells. Immature DCs, located in the basolateral pocket of M cells or in the subepithelial dome directly beneath the FAE of the PP, can phagocytose and present these delivered antigens to induce effector T cell responses. M cell-mediated antigen delivery and induction of mucosal immune responses towards certain bacteria and other luminal antigens seem to rely heavily on this passage. Recently, goblet cells were also implicated as transporters of luminal antigens to DCs in the LP.

In addition, it has been suggested that immune cells in the lamina propria are capable of directly sampling luminal antigens, by extending dendrites between epithelial cells to reach antigens in the lumen. This capacity was shown to depend on the chemokine receptor CX3CR1, and was initially ascribed to dendritic cells. However, recent evidence demonstrate that the majority of CX3CR1+ cells in the intestinal lamina propria are tissue-resident macrophages; it is therefore more likely that the dendrite-extending cells are macrophages rather than DCs. In line with this, intraepithelial CD103+ DCs were shown to be poor at sampling luminal antigens as compared to tissue resident macrophages. Furthermore, it has been suggested that macrophages that have acquired antigens via transepithelial dendrites can transfer these antigens to lamina propria DCs, via gap junctions. Thus, lamina propria DCs can acquire luminal antigens by a variety of mechanisms, although the entire mechanism of how antigen uptake occurs is not fully understood.
2. Dendritic cells

2.1 Introduction

The discovery of DCs was made by Steinman and Cohn in the early 70’s. Their work laid the foundation for DC biology for decades to come, and awarded Ralph Steinman Alfred Nobel’s prize in Medicine or Physiology in 2011. DCs were defined by their stellate morphology and their functional distinction from macrophages, and later studies have revealed these cells as critical players for initiation of adaptive T cell responses. In addition, Janeway’s ideas about self and non-self-antigen recognition also contributed to DC biology research.

DCs can be grouped into two separate lineages, conventional DC (cDC) and plasmacytoid DCs (pDCs), based on ontogeny, transcription factor (TF) dependency and functionality. The identification of cDCs has been far from simple, and many of the markers originally used to separate cDCs from other immune cells, in particular macrophages, are in fact redundantly expressed by several cell types. Thus, both cDCs as well as macrophages express MHC-II and the integrin CD11c. However, the use of a broader panel of markers has allowed distinction between these cell types. Thus, macrophages express F4/80, CX3CR1 and CD64. In contrast, cDCs are MHC-II+ CD11c+ but lack expression of F4/80 and CD64, and do not express high levels of CX3CR1. In addition, some cDCs can be identified by their expression of CD103. Finally, in contrast to macrophages, cDCs can express the chemokine receptor CCR7 which allows them to migrate to the MLN where they can induce T cell activation and promote effector T cell migration to the intestinal mucosa by induction of gut-homing receptor expression.

cDCs can be further divided into phenotypically and functionally distinct subsets. However, because surface marker expression may vary depending on activation status and localization, grouping cDCs based on their lineage commitment or requirement for certain transcription factors has been suggested to be a far more suitable method. Using this strategy, cDCs can be separated into two distinct lineages, cDC1 and cDC2, which depend on the transcription factors IRF8 and IRF4, respectively. Moreover, cDC1 and cDC2 cells can be further distinguished based on their respective expression of XCR1 and SIRPα.
2.2 Development of dendritic cells

DC progenitors are found in the bone marrow (BM) where they mature from hematopoietic stem cells into precursor cDCs (pre-cDC) in a series of intermediate precursors, including common monocyte progenitors (CMP), monocyte-macrophage DC progenitor (MDP) and common dendritic cell progenitor (CDP). The monocyte/DC axis separates when CDPs diverge from the MDPs, losing monocyte potential but allowing pDC and cDC development. CDPs can develop towards either pre-pDCs or pre-cDCs, while later committed cDC precursors lack monocyte and pDC potential. Originally, cDC1 and cDC2s were thought to develop into mature subsets after travelling via the blood to peripheral tissue where they would undergo Flt3L-dependent expansion and differentiation into fully mature subsets; however, recent evidence suggests that the commitment to each branch might occur in the BM, already at the CDP stage, and with cDC1- and cDC2-specific progenitors (Fig 1). Consistently, recent studies identified IRF8 as a critical terminal selector for the maintenance of terminally differentiated cDC1s (Fig 1).

ZBTB46 is currently the only transcription factor that separates committed cDCs from other mononuclear phagocytes. The distinct expression of Zbtb46 in cDCs was defined in Zbtb46-DTR mice, which display inhibited development of all cDC subsets. Zbtb46 gene expression is initiated in pre-cDCs, and maintained in subsequent differentiated cDC subsets. The mechanism by which Zbtb46 allows for commitment to the cDC lineage is mediated, at least in part, by restricting the expression of myeloid growth factor receptors and thus only allowing cDC commitment. cDCs also require certain growth factors for their development and maturation process. The development of cDCs is dependent on the growth factors GM-CSF and Flt3L, and mice which are either Flt3L-deficient or receive Flt3L inhibitors have severely reduced numbers of cDCs and pDCs. Development of cDCs from BM cells in vitro can be accomplished by addition of Flt3L or GM-CSF. While GM-CSF is required for the development of cDCs in peripheral tissue, it does not seem to be important for lymph node (LN)-resident cDCs.
Figure 1. Development of the cDC1 and cDC2 lineage

cDCs develop in a series of events, including the development of common DC progenitors (CDP) from macrophage DC progenitors (MDP), which further develop into pre-cDCs. Lineage commitment to cDC1 and cDC2s is suggested to occur in the BM and not in the periphery, as previously thought.
2.3 Dendritic cell activation, maturation and migration

Pre-cDCs leaving the BM can localize to lymphoid organs to become lymph node-resident cDCs, or enter peripheral organs such as the intestine where microenvironmental cues induce expression of distinct surface markers. LN-resident and migratory cDCs can be separated based on the level of expression of MHC-II, with LN-resident cDCs having intermediate expression of MHC-II (MHC-II\textsuperscript{int}), while cDCs that have migrated from the tissues to local LNs are defined by their high expression of MHC-II (MHC-II\textsuperscript{hi}). Immature DCs are efficient at sampling antigens, while being less efficient at antigen-presentation. cDCs mature in a series of events, initiated upon sampling of the environment through PRRs such as TLRs, in addition to the process of antigen uptake and processing. The maturation process involves upregulation of the antigen-presenting molecules MHC-I and –II and costimulatory molecules, including CD80, CD86 and CD40. In addition, maturation also induces increased expression of the chemokine receptor CCR7 on the surface of cDCs, which allows their recruitment from the periphery, via afferent lymphatics, to the T cell area of the draining lymph nodes by expression of the CCR7 ligands CCL19 and CCL21, released by lymphatic endothelial cells and LN stroma cells.

2.4 T cell activation

Activated DCs in the periphery migrate to associated lymphoid tissue and LNs where they present antigen to naïve T cells. Activation of naïve T cells and differentiation of effector cell subsets require three signals. Signal 1 and 2 are provided by the antigen-presenting DC, in the form of antigenic peptide/MHC, and costimulatory molecules, respectively, expression of which are upregulated following signalling via pattern recognition receptors. Cytokines, derived either from the antigen-presenting DC or adjacent cells, and typically referred to as “signal 3”, determines the type of effector T cell response induced. CD4\textsuperscript{+} T helper cells can in this way differentiate into Th1, Th2, Th17, Tfh and Treg cells. In addition, DCs also induce the capacity of effector T cells to home to the relevant tissue, by induction of tissue-specific homing receptor expression during T cell activation.

T helper cell effector responses can be tailored towards the type of infection giving rise to T cell activation. Thus, Th1 cells have the important task of eradicating intracellular pathogens, e.g. by producing IFN-γ that has the ability to activate microbicidal activity in macrophages and by inducing isotype class switching to IgG2a/IgG2c. Differentiation of Th1 cells requires IL-12-production by the
antigen-presenting cell,\textsuperscript{125} which drives generation of the transcription factor T-bet and in turn mediates IFN-\(\gamma\) production.\textsuperscript{126} Th2 cells, on the other hand, are associated with multicellular parasite infection, and may also play a pathogenic role during asthma and allergic reactions.\textsuperscript{127,128} Th2 cells produce the effector cytokines IL-4, IL-5 and IL-13, which can regulate the function of various immune and non-immune cells, and promote class switching to IgG1 and IgE.\textsuperscript{123,124,129–131} Th2 cell development from naïve CD4 T cells is promoted by signalling via the IL-4R, which leads to activation of STAT6 that promotes expression of the Th2-associated transcription factor GATA3.\textsuperscript{132–137} Production of IL-4 by T cells is further regulated by the transcription factor c-Maf,\textsuperscript{138,139} which promotes Th2 differentiation through an IL-4-dependent mechanism.\textsuperscript{140} Finally, Th17 responses are typically associated with infection with fungi and certain extracellular bacteria.\textsuperscript{141} In addition, Th17 cells have also been shown to be involved in the pathogenesis of IBD, multiple sclerosis and rheumatoid arthritis.\textsuperscript{142} Th17 cells produce the signature cytokine IL-17, which e.g. mediate neutrophil recruitment, and IL-22 that can protect the intestinal epithelium upon injury or infection by bacteria.\textsuperscript{143,144} Development of Th17 cells is driven by the transcription factor ROR\(\gamma\)\textsuperscript{t}\textsuperscript{145} and require TGF\(\beta\),\textsuperscript{146} and occasionally IL-6.\textsuperscript{147,148} In addition, IL-23\textsuperscript{149} and IL-1\(\beta\) can reinforce an ongoing Th17 response.\textsuperscript{148} Finally, the signature cytokines produced by some of these subsets, such as those derived by Th1 and Th2 cells, can antagonize the differentiation and function of the other subsets,\textsuperscript{126,150,151} demonstrating the delicate balance between the ratio of these polarizing cytokines.

In addition to Th1, Th2 and Th17 cells that localize to peripheral tissues to exert their effector functions, T helper cells can also differentiate into FoxP3-expressing regulatory T cells (Treg) and T follicular helper cells. Tregs promote regulation and maintenance of peripheral tolerance to prevent autoimmune diseases and inflammatory conditions e.g. by production of IL-10 and TGF\(\beta\)\textsuperscript{152}, while Tfh cells provide help during B cell activation.

### 2.5 Intestinal dendritic cells

In addition to being divided into cDC1 and cDC2 cells, cDCs in the intestinal lamina propria can also be defined and subdivided by their expression of the integrins CD103 and CD11b, into four distinct subsets: CD103\(^-\)CD11b\(^-\) (CD103 SP), CD103\(^+\)CD11b\(^-\) (DP), CD103\(^-\)CD11b\(^+\) (CD11b SP) and CD103\(^+\)CD11b\(^+\) (Fig 2).\textsuperscript{153} These subsets are unevenly dispersed along the intestinal mucosa,\textsuperscript{59,64,101} with DP DCs found at highest frequency in the small intestine, while CD103 SPs are more numerous in the colon.\textsuperscript{64,73} DP and CD103 SP DCs are the major populations of cDCs in the small intestinal lamina propria, accounting for 85-90% of migratory
cDCs. In contrast, DP cDCs only account for a minor population of migratory cDCs in the colon, with CD103 and CD11b SPs being the major cDC populations. All four subsets are able to migrate from the intestinal lamina propria to the ascending draining MLN where they prime naïve T cells.

Figure 2. Intestinal cDC subsets and their transcription factor dependency.
Schematic overview of the major cDC subsets found in the small and large intestinal lamina propria and MLN, and their dependency on distinct transcription factors for their development.

2.6 Irf8 and Irf4-dependent cDC1s and cDC2s

IRF8-dependent cDC1s

CD103 SP cDC in the intestine mucosa express XCR1, and are classed as cDC1 cells. Development of cDC1s depend on the transcription factors Batf3, IRF8 and Id2; hence, cDC1s express Batf3 and IRF8, and are completely absent in BAFT3<sup>−/−</sup> and IRF8<sup>−/−</sup> mice. Several surface markers have been associated with cDC1 cells in addition to CD103<sup>+</sup>CD11b<sup>+</sup> including CD8α<sup>+</sup>, XCR1<sup>+</sup> and DNGR1. The chemokine receptor XCR1 is a highly specific marker and particularly useful marker for cDC1s as it is expression by human as well as mouse cDC1s. Although DNGR1 has also been proposed as a useful marker for their definition, it is however also expressed by all committed cDC precursors. cDC1s found in lymphoid organs such as LNs and the spleen express CD8α.
cDC1s are acknowledged for their efficient presentation of antigens to CD8⁺ T cells and as a source of IL-12 during both steady-state conditions as well as during infection or immunological challenge, which is required for efficient Th1 responses. Additionally, cDC1s are critical for tolerogenic responses, accomplished by their superior ability to generate TGFβ and induce Tregs. Thus, cDC1s express high levels of the TGFβ-activating integrin αvβ8, which is required for the maturation of inactive TGFβ to its active form. Mice with a DC-specific deficiency in αvβ8 develop colitis because of, at least in part, the inability of these DCs to induce or maintain Tregs. CD103⁺ are also efficient producers of retinoic acid (RA), which is required for the generation of Tregs, and critical needed for the imprinting of gut homing molecules on T cells.

IRF4-dependent cDC2s

While cDC1 cells in the intestinal mucosa and associated lymphoid tissues appear to consist of one uniform population, cDC2s can be divided into DPs (CD103⁺ CD11b⁺) and CD11b SPs (CD103⁻ CD11b⁺), based on their surface marker expression. cDC2s can also be defined by expression of SIRPα. cDC2s depend fully or partially on Irf4, Notch2, Zeb2 and Klf4 for their development. IRF4 has a critical role for the homoeostasis of DPs in the intestinal mucosa by regulating the development and survival of this subset. In contrast to IRF8, which is critical for the development of cDC1, mice with a CD11c-specific deletion of IRF4 retained a population of DP cDCs in the intestinal lamina propria, although at lower numbers, while the number of DP cDCs in the MLN was severely reduced. This was shown to be due to impaired survival of DP cDCs in the absence of IRF4 expression. Similarly, mice with Notch2- or KLF4-deficiency in CD11c⁺ cells display a reduced frequency of intestinal DPs, while DPs remain unaffected by deficiency in IRF8 or Batf3. IRF4 is also required for the functionality of cDCs, including during the migration of cDCs from the skin to the draining lymph nodes via CCR7 and for antigen presentation via the MHC-II complex. Although DP cDCs are capable of presenting antigens to CD8⁺ T cells, they preferentially express antigens to CD4⁺ T cells. Consistently, IRF4-competent, but not IRF8-competent cDCs, are able to efficiently prime OT-II cells upon OVA administration in vivo. Furthermore, cDC2 appear to be preferentially involved in the generation of adaptive Th17 and Th2 responses. Hence, mice with deficiency of IRF4, SIRPα, or Notch2 in CD11c⁺ cells have impaired intestinal Th17 responses during steady state, while mice with a KLF4-deficiency display aberrant Th2 responses upon infection or immunization with S. mansoni soluble egg antigens (SEA).

While CD11b SPs appear to be partly dependent on IRF4, as demonstrated by the reduction of this population in mice with IRF4-deficient CD11c⁺ cells, they are
most likely Notch2-independent.\textsuperscript{187,191} Compared to DPs, CD11b SP DC express higher levels of SIRP\(\alpha\) in the MLN and intermediate levels of CX\(_3\)CR1.\textsuperscript{154} Recently, Zeb2-deficiency in CD11c\(^+\) cells was shown to be important for the development of CD11b SPs in the intestine, by repressing expression of Id2 that is associated with development of cDC1 cells.\textsuperscript{195} Furthermore, a proportion of CD11b SPs express the monocyte-associated chemokine receptor CCR2.\textsuperscript{194} CCR2 is well-known for its role during egress of Ly6C\(^{hi}\) monocytes from the BM;\textsuperscript{196} however, CCR2\(^+\) CD11b SPs in the MLN represents true cDCs and do not derive from Ly6C\(^{hi}\) monocytes.\textsuperscript{194} CCR2\(^+\) CD11b SPs are found in both human and mouse intestine and are involved in driving Th17 responses,\textsuperscript{194} which is consistent with the observation that KLF4-deficient mice have normal Th17 responses but reduced numbers of DPs, indicating that Th17-induction is indeed IRF4-dependent but may not depend entirely on the DP cDC subset.
3. Trichuris muris

3.1 Introduction

Intestinal helminth infections cause severe health issues in over 1 billion people worldwide, with children being the most targeted group. Over the past fifty years, infection of rodents with the gastrointestinal nematodes *Nippostrongylus brasiliensis*, *Heligmosomoides polygyrus*, *Trichinella spiralis* and *Trichuris muris* have served as valuable models to study the induction of adaptive immunity and parasite expulsion mechanisms. *T. muris* is a large intestinal nematode parasite, closely related to the major human pathogen *T. trichiura* that infect approx. 500 million people worldwide. Similar to many other nematode infections, successful immune responses to *T. muris* infection relies on induction of a Th2 response, in particular by the production of the cytokine IL-13, which ultimately leads to expulsion of the worm prior to adulthood. The Th2 response promotes a variety of effector responses by cells in the local tissue, for example increased epithelial turnover, goblet cell hyperplasia and enhanced mucus production, which together create an unfavourable niche for the parasite. Induction of adaptive type 2 responses to *T. muris* infection occurs primarily in the local intestine-draining mesenteric lymph nodes, and is thought to be mediated by migratory cDCs that localize to these organs after acquiring parasite-derived antigens in the infected tissue, although the precise mechanism by which adaptive Th2 responses are induced, and the role of cDCs and cDC subsets in this process, is not yet fully understood.

*T. muris* infection is initiated upon ingestion of infectious eggs and proceeds with larvae hatching in the caecum – a process that in mice depends on the presence of bacteria, and is mediated at least partly by bacterial type 1 fimbriae. Next, the anterior end of the larvae invades the epithelial layer of the caecum and proximal colon. This is likely facilitated by the secretion of proteases from the stichosome, an organ in the anterior part of the worm, which can degrade mucins and extracellular matrix proteins. The worms form so called syncytial tunnels by burrowing through adjacent epithelial cells, where they remain embedded throughout their entire life cycle. Early studies of *T. muris* excretory/secretory (E/S) antigens revealed that soluble antigens from the anterior end of adult worms were the most immunogenic as compared to the posterior end.
and whole larvae.\textsuperscript{220} In addition to the mucus-degrading proteases, one of the best categorized proteins in \textit{Trichuris} E/S is a pore-forming protein.\textsuperscript{221} E/S antigens from swine-specific \textit{T. suis}, are capable of degrading the tight junction proteins between intestinal epithelial cells and in this way weakening the epithelial barrier integrity,\textsuperscript{222} however a potential similar function of \textit{T. muris} E/S antigens remains to be demonstrated. Finally, while parasite-derived products from other nematodes have been suggested to have a direct Th2-inducing capacity, such as for example products in \textit{S. mansoni} SEA,\textsuperscript{223,224} no direct such capacity has been shown for \textit{T. muris}-derived E/S antigens.

\section*{3.2 Resistance & Th2 responses}

The adaptive immune response towards \textit{T. muris} infection can be of either a Th1 or Th2 type and is determined by several factors including genetic background and infection dose. The genetic background of the infected host is an essential determinant for the outcome of resistance or susceptibility and is driven by MHC-II-linked genes. Alleles promoting either resistance, H-2q, or susceptibility, H-2k, during infection are found in the I-A region.\textsuperscript{225–228} The infection dose is also a determinant in the regulation of adaptive immune responses to \textit{T. muris} infection. Thus, the nature of the ensuing adaptive response can be intentionally modulated by infection with a high (typically 100-400 eggs) or low dose (20-40) of eggs, with high dose resulting in generation of a Th2 response and resistance, while low dose infection of normally resistant C57BL/6 and BALB/c mice results in induction of a Th1 response and chronic infection.\textsuperscript{229,230} Interestingly, trickle infections, i.e. repeated low dose infections, which are thought to better mimic the parasite exposure in infected humans, leads to the build-up of a large enough egg load to drive induction of a Th2 response and expulsion,\textsuperscript{231} with a similar phenomenon also seen in wild-living mice.\textsuperscript{232}

Resistance to infection is associated with type 2 immunity and consequently characterized by production of the cytokines IL-4, IL-5, IL-9 and IL-13,\textsuperscript{204,233–237} which promotes protective immunity through several mechanisms. IL-4 and IL-13 share the usage of the IL-4R\(\alpha\) receptor,\textsuperscript{235,238,239} which has been shown to be a critical for initiation of protective Th2 responses during infection with \textit{T. muris}.\textsuperscript{237,240} Thus, antibody-mediated blockade of the IL-4 receptor prevented expulsion, associated with increased IFN\(\gamma\) levels, while reduced levels of Th2-associated cytokines.\textsuperscript{237,241} The role of IL-4 was further supported by experiments conducted in genetically susceptible AKR mice, which became resistant when administered with an IL-4 complex, containing a mixture of rIL-4 and anti-IL-4 mAb.\textsuperscript{237} Interestingly however, while IL-4 deficiency in C57BL/6,\textsuperscript{233} and male
BALB/c mice\textsuperscript{234} rendered the mice susceptible to infection, IL-4-deficient BALB/c females remained capable of mediating expulsion, due to production of high levels of IL-13.\textsuperscript{234} The same study found that IL-13-blockade in resistant IL-4-deficient BALB/c females prevented expulsion, while IL-13 administration to IL-4 knock-out males induced resistance.\textsuperscript{234} However, while both IL-4 and IL-13 are involved in the Th2 response, IL-13 appears to be more directly involved in mediating worm expulsion. The production of IL-13 drives several responses by the colonic epithelium that promotes expulsion, including goblet cell hyperplasia and mucus production.\textsuperscript{233,241,242} Additionally, IL-13 also positively regulates epithelial cell turnover,\textsuperscript{205} in balance with IFN$\gamma$, which promotes enhanced epithelial differentiation within the crypts of Lieberkühn in the large intestine.\textsuperscript{243} Similarly, IL-9 has also been suggested to be involved in the effector response to \textit{T. muris}, by induction of smooth muscle contractility that contributes to a more efficient expulsion of \textit{T. muris} worms.\textsuperscript{235}

3.3 Chronicity & Th1 responses

Chronic infection with many human\textsuperscript{244} and rodent parasites\textsuperscript{245} is often associated with adaptive Th1 responses, with a beneficial outcome for the parasite in which it is able to stay within its host and reproduce. Consistently, adaptive responses to chronic \textit{T. muris} infection in susceptible mice, such as AKR mice, are characterized by production of the typical Th1-associated cytokines IFN$\gamma$, IL-12 and IL-18.\textsuperscript{229,237,246–251} The role of these cytokines in the establishment or maintenance of chronicity has been elegantly demonstrated in studies using administration of either blocking antibodies or recombinant cytokines. Thus, genetically susceptible AKR mice became resistant and expelled parasite worms upon IFN$\gamma$ neutralization.\textsuperscript{237} IL-12 is similarly important for Th1 responses during infection, as IL-12 administration led to the establishment of chronicity and increased worm burden in normally resistant mice.\textsuperscript{248} Interestingly, depletion of IFN$\gamma$ in IL-12-treated mice inhibited chronicity, demonstrating that IL-12-mediated chronicity was dependent on IFN$\gamma$.\textsuperscript{248} IL-18 has also been proposed to regulate Th1 responses in \textit{T. muris}-infected mice as IL-18-deficient mice are resistant to infection\textsuperscript{247}. However, the role of IL-18 appear to be more associated with downregulation of IL-4 and IL-13, and does not rely on the capacity to induce IFN$\gamma$, as demonstrated by unaltered IFN$\gamma$ levels upon IL-18 administration, while reduced levels of IL-13 and induction of resistance.\textsuperscript{247}
3.4 Induction of adaptive immunity to *T. muris* infection

### 3.4.1 The role of the intestinal epithelium

The immune response to *T. muris* is first initiated at the intestinal epithelium, the first host cell type targeted during infection. However, already the mucus barrier covering the epithelial layer in the intestine plays an important role during infection with *T. muris*. The type 2 response to infection is associated with IL-13-induced goblet cell hyperplasia, and increased production of Muc2, the dominant mucin type under normal conditions, in resistant but not susceptible mice. Moreover, the protective response in resistant mice is also associated with production of Muc5ac, a mucin normally not found in the intestinal mucosa, also under the control of IL-13. Importantly, Muc5ac-deficient mice are unable to expel worms despite an ongoing robust Th2 response, demonstrating that the Th2 response is insufficient for expulsion to occur when the mucous barrier is deprived of Muc5ac. Recent studies also suggest that mucin sulphation, regulated by IL-13, promotes expulsion by modification of the mucin so that it becomes less vulnerable for degradation by parasite-derived E/S antigens, thus further high-lighting the importance of a protective mucus layer.

Because of the close association of *T. muris* worms and their intestinal epithelial niche, it is not surprising that various studies have highlighted a critical role for the epithelium in the direction of type 2 responses. Although larvae never breach the basement membrane and lives in close contact with the intestinal epithelium in so called syncytial tunnels, they must re-invade new epithelial cells at the apical side to maintain their niche. PRR are found throughout the epithelium and act as important sentinels responsible for recognizing foreign PAMPs, yet, no *T. muris*-associated PAMP or corresponding critical PRR has yet been identified. However, a role for TLR4 and Myd88 signalling has been suggested during chronic *T. muris* infections. Although the underlying mechanism is yet to be determined, it was suggested that TLR4-induced MyD88 signalling was triggered in response to luminal bacteria due to the reduced epithelial integrity. Finally, protective immunity to *T. muris* has been demonstrated to involve NF-κβ activation in epithelial cells, as mice with a loss of NF-κβ signalling in intestinal epithelial cells via a deletion of IKK-β, the catalytic subunit needed for NF-κβ signalling, were susceptible to *T. muris* infection, although the trigger(s) and pathway(s) leading to NF-κβ activation remains to be determined.

The intestinal epithelium is an important regulator of the immune response upon activation by production of chemokines and cytokines that subsequently act by recruiting and activating immune cells. Several chemokines have been implicated during infection with *T. muris*. The expression of the chemokines CCL2, CCL3,
CCL5 and CCL20 are increased in resistant, but not in susceptible mouse strains, and have been shown to attract DCs to migrate towards the epithelial layer in the colon of resistant mice. Furthermore, expression of CCL2 is reduced in Myd88−/− mice, and CCL2−/− mice fail to expel parasite worms and display reduced levels of IL-4, while increased levels of IL-12. Epithelial-derived cytokines may also contribute to the induction of appropriate immune responses during nematode infection. The epithelial-derived cytokines IL-25, IL-33 and TSLP have been demonstrated to play an important role for induction of Th2 responses during infection with *T. muris*. Thus, TSLP promote Th2 responses, as demonstrated by studies showing delayed expulsion and reduced Th2 cytokines following administration of anti-TSLP antibodies or using TSLP-R deficient mice. Similarly, IL-25 knock-out (KO) mice were susceptible to infection and displayed reduced Th2 cytokine responses, while IL-25 administration to normally susceptible AKR mice was sufficient to confer resistance, suggesting that IL-25 is also of importance for protective responses against *T. muris* infection. Furthermore, IL-25 promotes the production of IL-4, IL-5 and IL-13, as demonstrated by the increased secretion of these cytokines, by Th2 cells and ILCs, in lung and intestinal tissue of mice upon administration of IL-25. Recently, epithelial tuft cells were suggested to be the dominant source of IL-25 in the intestine, which could be further enhanced during infection with the nematodes *H. polygyrus*, *N. brasiliensis* and *T. spiralis*. IL-25 promotes the production of IL-4, IL-5 and IL-13, as demonstrated by the increased secretion of these cytokines, by Th2 cells and ILCs, in lung and intestinal tissue of mice upon administration of IL-25. However, the role of tuft cells in production of IL-25 during *T. muris* infection has not yet been investigated. In addition to TSLP and IL-25, type 2 responses can also be activated upon release of the alarmin IL-33. Moreover, IL-33 is upregulated early during *T. muris* infection in resistant mice, and has been shown to induce expulsion during infection with some but not all intestinal parasite infections. Thus, epithelial-derived mediators are critical players in bridging the innate immune response with adaptive responses, by secreting cytokines and chemokines, which can attract DCs and, directly or indirectly, promote initiation of protective Th2 responses.

### 3.4.2 Innate type 2 responses and other type 2-accessory cell types

While it is clear that *T. muris* infection causes the production of epithelial cytokines, including IL-25, IL-33 and TSLP, the target cells of these cytokines are not clear. The release of epithelial-derived cytokines is known to influence the function of various cells in the lamina propria, including DCs and ILC2s. ILC2s lack antigen-specific receptors but can instead be activated in response to epithelial cytokines, and in turn promote immunity by production of type 2 cytokines, in particular IL-5 and IL-13. Because of their exceptional ability to initiate and amplify type 2 responses...
responses, ILC2s have been implicated during infection with several helminth parasites.\textsuperscript{263,279–284} While their contribution during infection with \textit{T. muris} is not yet clear, a population of so called MMP\textsuperscript{type2} cells, defined as Lin\textsuperscript{−} Sca-1\textsuperscript{+} and c-kit\textsuperscript{int}, were shown to be important for protective responses during \textit{T. muris} infection,\textsuperscript{263} although it remains to be determined if these cells are true ILC2s.

Mast cells, basophils and eosinophils have the capacity produce IL-4, and may be involved during induction of Th2 responses.\textsuperscript{285–291} In fact, basophils were suggested to act as antigen-presenting cells during \textit{T. muris} infection,\textsuperscript{292} although later studies has demonstrated that DCs are critical for induction of Th2 responses following \textit{S. mansoni} infection,\textsuperscript{293} suggesting that basophils are more likely to play an accessory role during induction of Th2 cells. Mast cells play an important role for the protection against a range of intestinal parasites, including infections with \textit{N. brasiliensis},\textsuperscript{294} \textit{H. polygyrus bakeri}\textsuperscript{295} and \textit{T. spiralis}.	extsuperscript{296–298} While initially shown to be dispensable for \textit{T. muris} expulsion,\textsuperscript{299} more recent studies have suggested that they may play a role in the initiation of optimal Th2 responses.\textsuperscript{300} In addition, mast cells accumulate in the colonic epithelium during high dose \textit{T. muris} infection and remain there after worm expulsion, indicating a potential role of these cells during the resolution phase.\textsuperscript{301} Finally, while IL-4-producing eosinophils are found at increased frequencies in both the MLN and colon during \textit{T. muris} infection they are dispensable for generation of Th2 responses and worm expulsion.\textsuperscript{291,302}

### 3.4.3 The role of DCs

While DCs have been implicated in several helminth infection models,\textsuperscript{303} including infection with \textit{S. mansoni} and \textit{H. polygyrus},\textsuperscript{293,304,305} the role of cDCs during infection with \textit{T. muris} has so far been inadequately examined. Previous experiments have demonstrated accumulation of a population of CD11c\textsuperscript{+} B220\textsuperscript{−} cells, suggested to be DCs, in the MLN during \textit{T. muris} infection.\textsuperscript{211} Furthermore, CD103\textsuperscript{+} DC are recruited to the colonic epithelium in response to epithelial-derived chemokines selectively in resistant mice.\textsuperscript{213,306} More recently, SHIP-1, which regulate the PI3K pathway, was shown to be crucial in DCs for protective Th2 responses during \textit{T. muris} infection, as demonstrated by increased IL-12 production by DCs,\textsuperscript{307} however, the role for SHIP-1 in DCs has not yet been determined in depth.

Thus, given the gap in our knowledge on the role of DCs during \textit{T. muris} infection, the aim of this thesis has been to investigate the contribution of cDC and cDC subsets in the induction of adaptive immune responses to chronic or acute \textit{T. muris} infection.
Aims of this thesis

The overall aim of this thesis has been to study the role for conventional dendritic cell subsets in the generation of adaptive Th1 and Th2 responses during acute and chronic infection with the gastrointestinal nematode *Trichuris muris*. More specifically, my aims were:

- To determine the role of IRF4-dependent cDCs in the generation of adaptive Th2 responses during acute infection with *T. muris*, through high-dose infections in *CD11c-cre.Irf4^{flox/flox}* mice, which have a substantial reduction of intestinal CD103⁺CD11b⁺ cDCs.
- To determine the role of IRF8-dependent cDCs in the generation of adaptive Th1 responses during chronic infection with *T. muris*, through low-dose infections in *CD11c-cre.Irf8^{flox/flox}* mice, which lack intestinal CD103⁺CD11b⁻ cDCs.
- To assess the immune response to *T. muris* infection in the combined absence of the transcription factors IRF4 and IRF8 in CD11c⁺ cells, by low-dose infections of bone marrow-chimeric *CD11c-cre.IRF4^{flox/flox}.IRF8^{flox/flox}* mice.
5 Summaries of papers I-III

Paper I:

*IRF8 Transcription-Factor-Dependent Classical Dendritic Cells Are Essential for Intestinal T Cell Homeostasis.*

**Background/Aim:**
IRF8-dependent CD103⁺ CD11b⁻ DC represent one of the major cDC populations in the small and large intestinal mucosa. Despite this, the role of IRF8-dependent cDC in intestinal homeostasis and during induction of adaptive immune responses in intestinal-draining MLN remain largely unknown. Here, we utilized mice with a CD11c-specific deletion of IRF8 to examine the consequence on immune cell homeostasis, and on induction of adaptive T cell responses following antigen immunization and during live infection with the gastrointestinal nematode *T. muris*.

**Results:**
- CD11c-cre.*IRF8*<sup>fl/fl</sup> mice lack CD103⁺CD11b⁻ cDC in the small intestinal lamina propria and MLN, and CD8α⁺ lymph node-resident cDC
- CD11c-cre.*IRF8*<sup>fl/fl</sup> mice displayed dramatically reduced numbers of CD45⁺ IEL, including CD8αβ⁺ TCRαβ⁺ and CD4⁺ TCRαβ⁺ IELs, and fail to generate CD4⁺CD8αα⁺ IELs due to the absence of β8 integrin-expressing IRF8-dependent cDC
- CD11c-cre.*IRF8*<sup>fl/fl</sup> mice display impaired cross-presentation and induction of gut-homing receptors on CD4⁺ and CD8⁺ T cells
- CD11c-cre.*IRF8*<sup>fl/fl</sup> mice display reduced numbers of IFNγ⁺ cells in the small intestinal lamina propria, and impaired generation of Th1 cells in the MLN
- Finally, CD11c-cre.*IRF8*<sup>fl/fl</sup> mice fail to support chronic infection and produce parasite-specific IgG2c antibodies following low dose-infection with *T. muris*
Discussion

TCRαβ IELs in the intestinal mucosa are tissue-resident memory T cells which may be equipped with cytolytic functions that can quickly react for the benefit to fight pathogens or curtail overt inflammatory responses, thus contributing to a maintained homeostasis. Here, we demonstrate a critical role for CD103⁺CD11b⁻ cDCs in the maintenance of CD8αβ⁺ and CD4⁺CD8αα⁺ IELs, as the numbers of these IEL subsets were severely reduced in mice deficient in IRF8-dependent cDC. The reduction of CD8αβ⁺ IEL was associated with an impaired capacity of IRF8-dependent cDC to cross-present antigens and induce gut-homing receptor expression on responding CD8⁺ T cells. In contrast, the reduced number of CD4⁺ CD8αα⁺ IEL was caused by the absence of β8 integrin, which is expressed selectively on IRF8-dependent cDC. β8-integrin can mediate activation of the biologically active form of TGFβ, which has previously been shown to be required for induction of CD4⁺ CD8αα⁺ IEL. Thus, IRF8-dependent cDCs are required for IEL homeostasis.

We also assessed the capacity to generate Th1 responses in the absence of IRF8-dependent cDCs. Strikingly, IFNγ⁺ T cells were almost absent in the intestinal lamina propria of IRF8-deficient mice, and Th1 induction was impaired in MLN. We therefore utilised low dose infection with T. muris to further investigate the induction of Th1 responses, as it is well known that chronic infection with T. muris is dependent on generation of a Th1 response and IFNγ production and promoted by IL-12, likely produced by the antigen-presenting cell. Mice deficient in IRF8-dependent cDCs failed to become chronically infected following low dose infection and, furthermore, failed to mediate isotype switching to IgG2c, a process known to be dependent on IFNγ, consistent with the impaired capacity to induce Th1 responses.

Taken together, these results demonstrate an essential role for IRF8-dependent cDCs in maintaining intestinal homeostasis, including an essential role for intestinal IEL differentiation and generation of Th1 cells during homeostasis as well as in an infection-context.
Paper II:

**Different populations of CD11b⁺ dendritic cells drive Th2 responses in the small intestine and colon**

**Background/Aim:**

Previous publications have demonstrated the importance of IRF4-dependent cDC in generation of intestinal Th17 responses.⁶⁹ In addition, several studies have suggested a role for IRF4-dependent DC in the induction of Th2 responses in the skin and respiratory tract.³¹¹–³¹³ In the current study, our aim was to examine the role of IRF4-dependent DC during induction of Th2 responses in the intestinal mucosa. Therefore, we investigated mice which harboured a targeted deletion of IRF4 selectively in CD11c⁺ cells in two complementary models to induce intestinal Th2 responses, subserosal injection of Th2-promoting SEA antigens³¹⁴,³¹⁵ and live infection with *T. muris*.

**Results:**

- IRF4-dependent cDCs were critical for induction of Th2 responses following subserosal injection of SEA and during high dose-infection with *T. muris*
- cDCs transported antigens and triggered CD4⁺ T cells responses in the MLN after subserosal antigen injection
- IRF4-deficient cDCs were capable of driving Th2 responses after transfer directly into the MLN
- The incapacity of CD11c-cre.*IRF4*⁰/⁰ mice to induce Th2 responses was associated with reduced numbers of antigen-carrying cDC in the MLN, while
- Distinct IRF4-dependent cDCs promoted Th2 response after antigen injection into the small intestine and colon

**Discussion**

While the mechanism of Th2 induction *in vitro* is relatively well characterized, much less is known about the cell types and mechanism(s) that promote Th2 responses *in vivo*. Our results show that IRF4-dependent cDCs are critical for Th2 responses in the intestine, which is consistent with the findings depicting these cells as critical for induction of Th2 responses in the skin and lung.³¹¹–³¹³ Following *T. muris* infection with a high dose, which normally induces a Th2 response in wild-type mice,³¹⁶ we found that IRF4-deficient mice were unable to clear the infection and displayed a marked reduction of Th2-associated cytokines in the MLN. Interestingly, previous reports have suggested that IRF4 expression in cDCs is
important for antigen presentation via MHC-II and in migration to draining lymph nodes, however, we show that IRF4-deficient cDCs can take up antigen and mediate T cell proliferation and Th2 induction. Instead, we find that the number of antigen-carrying cDCs in the MLN are fewer in mice with IRF4-deficient cDCs, which could stem from previously described observations that IRF4 regulates survival\textsuperscript{69,70} and migration\textsuperscript{192} of cDCs, and suggesting that the reduced Th2 response is due to limited amount of presented antigen. In addition, we found a surprising compartmentalization in the functionality of the two major IRF4-dependent cDC subsets, thus, while DP cDCs were critical for induction of Th2 responses in the small intestine, CD11b SP cDCs mediated this function in the colon,\textsuperscript{314} suggesting that functional differences between cDC subsets may not only be dictated by their intrinsic properties, but also through local microenvironmental cues.

Collectively, these results reveal that IRF4-dependent DCs are critical for the induction of intestinal Th2 responses in the small and large intestine of SEA-immunized mice and \textit{T. muris}-infected mice. Additionally, while DPs account for driving Th2 responses in the small intestine, CD11b SPs drive Th2 responses in the large intestine.
Paper III

Distinct DC subsets regulate adaptive Th1 and 2 responses during Trichuris muris infection.

Background/Aim:
In this paper, we aimed to extend our observations from paper I and II, to further characterize the role of cDC subsets in adaptive Th1 and Th2 responses during chronic and acute T. muris infection, and to examine the potential synergistic or antagonistic role of these cells during infection. Finally, we investigated the adaptive response in mice with a combined CD11c-specific IRF4- and IRF8-deficiency.

Results:
- cDC accumulate in the MLN following high, but not low dose-infection with T. muris
- Consistent with our previous findings, CD11c-cre.$\text{IRF4}^{fl/fl}$ mice displayed reduced Th2 responses at day 21 p.i. following high dose-infection with T. muris
- Mice lacking IRF8-dependent cDC failed to induce Th1 cells and support chronic infection following low dose infection, which was associated with a strong increase in Th2 cytokine production, suggesting a potential Th2 antagonistic function of IRF8-dependent DCs
- Bone marrow chimeric mice with a combined deletion of IRF4 and IRF8 in CD11c$^+$ cells induced Th2 responses and mediated worm expulsion following low-dose infection with T. muris, indicating that other antigen-presenting cells can compensate for the absence of IRF4-dependent DCs, in the concurrent absence of IRF8-dependent DCs

Discussion
Recent studies by us$^{68,314}$ and others$^{311-313,317}$ have implied that cDC1 and cDC2s are critical for generation of Th1 and Th2 responses, respectively, and that a potential balance between the two subsets might exists.$^{317}$ Our previous findings in paper I indicated a critical role for IRF8-dependent CD103 SP cDCs for the induction of chronic infection with T. muris, a phenotype which we confirmed in this paper and by demonstrating that IRF8-deficient mice failed to induce IFN$\gamma^+$ Th1 cells. In addition, interestingly, we found that a strong Th2 response developed in the absence of IRF8-dependent cDCs, suggesting that this subset may be involved in antagonizing Th2 responses. How the absence of one cDC subset may lead to polarization of the adaptive immune response in a certain direction remains to be
assessed, although it seems plausible that the absence of one cDC subset and its secreted mediators, may allow the remaining cDCs to drive T cell polarization. This is consistent with other studies, demonstrating that Batf3-dependent cDC1 are able to antagonize Th2 responses, by production of IL-12.317 The absence of CD103 SPs and, thus, their ability to generate active TGFβ is also a plausible explanation for the increased Th2 responses seen in these mice, as mice with TGFβ-deficient signalling in cDCs have enhanced Th2 responses and expel T. muris,318 similar to mice with IRF8-deficient DCs.68 Finally, and much to our surprise, we found that Th2 responses can develop in the absence of IRF4-dependent cDC, in the concurrent absence of IRF8-dependent cDCs. While the underlying mechanism of how Th2 responses develop in these mice remains elusive, these data indicate that other cells may promote Th2 responses in the absence of IRF4- and IRF8-dependent cDCs.
Adaptive T helper cell responses are critical for mediating sterilizing immunity and generation of immunological memory. The immune response against gastrointestinal parasite infections is mediated by numerous cell types, which form a complex network in order to mediate efficient immunity and protection, normally accomplished through the induction of Th2 responses. In contrast, secretion of classical Th1-associated cytokines is associated with detrimental outcomes for the host tissue, often with chronic infection as the ultimate outcome. cDCs are at the center of these responses, by first sensing the pathogen or its products, and secondly, by inducing an appropriate adaptive effector T cell response to ensure eradication of the pathogen. However, we still lack detailed understanding of the cellular and molecular requirements for induction of Th2 responses. Furthermore, given the recent identification of cDC subsets, each with a distinct ontogeny and function, additional studies are yet required to fully unravel the role of these cDC subsets in inducing different types of T helper cell responses. The current thesis contributes to this field, and extends prior knowledge about the role of cDC subsets in the generation of adaptive Th1 and Th2 responses, by demonstrating the requirement of IRF8- and IRF4 dependent cDCs in these processes, respectively.

cDC subsets, in addition to their role in inducing different types of T helper cell responses, have also been suggested to antagonize each other, by production of cytokines. Our data from paper III of this thesis is consistent with this hypothesis, as we detected increased secretion of Th2 cytokines in the absence of IRF8-dependent cDC1s. cDC1 cDCs are the major source of IL-12 in the MLN, which has the ability to directly inhibit the differentiation of Th2 cells, and studies in *Schistosoma mansoni* and *Heligmosomoides polygyrus* infection have identified a functional role of cDC1-derived IL-12 in dampening type 2 responses. In addition, cDC1s have the highest expression of the TGFβ-activating integrin αvβ8, required for the generation of active TGFβ. TGFβ signaling in cDCs might be accountable for inhibiting Th2 responses during *T. muris* infection, as infected mice which lack the TGFβ-activating integrin αvβ8 in CD11c+ cells have enhanced Th2 response and display expulsion upon infection. In line with this, αvβ8 is expressed by CD103 SPs, and the lack of these cells, and thus the generation of active TGFβ, leads to the absence of Th1 responses during low-dose infection with *T. muris* and instead induces Th2 responses – in this way TGFβ
signalling might be involved in antagonizing Th2 responses. Conversely, IRF4-dependent cDC2s may also have an antagonistic capacity. CD11b SP cDCs or macrophages have been suggested to be a major source of IL-23 during infection with *C. rodentium*, and IL-23 production was associated with dampened IL-12 production by CD103 SPs, consistent with a potential role of IL-23 in antagonizing Th1 responses. Although the role of IL-23 during *T. muris* infection remains unknown, it is plausible that IL-23 may also promote Th2 responses during infection with *T. muris*. Previous studies have indeed shown that IL-23 signalling can enhance Th2-polarization *in vitro*, as well as *in vivo*, demonstrated by either neutralization or transgenic over-expression of IL-23 or IL-23R. However, this concept has not been studied in the intestinal mucosa and thus remains largely unexplored in the context of intestinal Th2 responses.

With these studies implicating an essential role for specific cDC subsets for the induction of adaptive immune responses, another key question remains unanswered, and that is which environmental signals cDCs receive in order to initiate Th2 responses. Thus, clear mechanistic data on how DCs orchestrate Th2 polarization, and whether certain receptors on DCs are required for this process, remains to be determined. While the molecular requirements for induction of adaptive Th1 and Th17 responses are relatively well characterized, comparably little is known with regards to how Th2 responses are generated. Indeed, for Th2 responses, it wasn’t even clear that this induction was mediated by cDCs until quite recently. Thus, some studies have depicted basophils or ILCs, instead of DCs, as key antigen-presenting cells that could mediate Th2 differentiation. However, this idea was later dismissed in favour of studies that proved cDCs as critical also for adaptive Th2 responses.

Several hypotheses have been put forward as “the mechanism”, including those portraying Th2 responses as default responses triggered only when typical polarizing mediators mediating other types of adaptive responses, such as IL-12, were absent. This was however later dismissed when it became apparent that cDCs don’t necessarily drive Th2 responses by the mere absence of pro-inflammatory signals. One of the prevailing mechanisms is that the antigen itself may promote induction of a Th2 response. Currently, the most well-described Th2 inducing parasite-derived antigen is the *S. mansoni*-derived ribonuclease Omega-1, which binds to mannose receptors on DCs. *S. mansoni* soluble egg antigen-treated DCs promote induction of Th2 cells *in vitro* through the endonuclease Omega-1, which orchestrate degradation of mRNA and rRNA to inhibit protein synthesis and orchestrate DCs to induce Th2 polarization in a mannose receptor-dependent manner. However, to date, a corresponding Th2-inducing capacity has not been demonstrated for *T. muris*-derived E/S. Alternatively, while the mechanism of induction of Th1 responses through various PRRs on cDCs is comparably well-established, the potential existence of Th2-inducing PRRs remains more unclear.
Several PRRs, including TLR2 and -4, NOD1 and-2 and Fcγ receptors, have been depicted to control Th2 responses. The TLR2 ligand, Pam-3-Cys, induces reduced IL-12 secretion by DCs in vitro and favours Th2 differentiation via the ERK-cFos-pathway. In addition, low doses of inhaled LPS or HDM allergens signal through TLR4 on epithelial cells, leading to induction of Th2 responses. Additional studies have implicated the role for some NLRs, CLRs and Fcγ receptors (discussed in greater detail elsewhere), yet, these appear largely context-dependent and often leave out the molecular mechanism of Th2 induction via the DC, and do not include the mechanism of intestinal Th2 responses. The role of cDCs in Th2 induction may also be more indirect and occur, for example, via epithelial-derived cytokines and alarmins. The role for the epithelial-derived cytokines IL-25, IL-33 and TSLP have been demonstrated in various models and displayed as strong inducers of type 2 responses by directly or indirectly inducing and amplifying production of IL-4, IL-5, IL-9 and IL-13. Increased TSLP production have been found at barrier surfaces such as in the skin, respiratory tract and intestine upon pathogen invasion. TSLP-binding acts primarily on monocytes and DCs to induce STAT5 phosphorylation, leading to increased CD80 and CD40 in addition to the release of chemokines which attracts T cells, or through induction of NF-κB, leading to upregulation of OX40L and secretion of CCL17. Additionally, TSLP may also be involved in antagonizing Th1 responses, by suppression of the p40 subunit of IL-12 which is associated with promoted Th1 responses. However, the full details of how intestinal cDCs may be regulated by epithelial-derived cytokines is yet to be explored.

While our studies have shed some light on the role of distinct cDC subsets in the regulation of adaptive immunity against intestinal nematode infection, further studies need to assess the potential interplay and antagonism between these subsets, in addition to determining the molecular pathways underlying induction of adaptive Th2 responses.

De vita blodkropparna som utgör immunförsvaret måste inte bara lära sig att svara gentemot inkärtare utan också lära sig att behålla lugnet mot ofarliga ämnen. När de vita blodkropparna inte klarar av att skilja farligt från ofarligt kan sjukdom uppstå. Sjukdomar såsom astma, allergi och inflammatoriska tarmsjukdomar är på stadig uppgång i vår del av världen och är ett resultat av att immunförsvaret aktiverats felaktigt.

Fokus för denna avhandling har varit att studera dendritiska celler (DC), en typ av medfödd immunförsvarscell som finns i nästan alla kroppens vävnader. DCs i tarmslumhinnan har som uppgift att fånga upp främmande ämnen, s.k. antigen, och förflytta sig från vävnaden i tarmen till lymfknutor där de kan presentera antigen för T-celler, vilka utgör en del av det adaptiva immunförsvaret. De T-celler som känner igen antigen som presenteras aktiveras och utvecklas till olika ”effektorceller”, såsom Th1 och Th2, vilka är anpassade till att bekämpa olika typer av infektioner. Under infektion med *T. muris* är det fördelaktigt att Th2-celler aktiveras, vilka har förmågan att bekämpa parasiter, medan Th1-celler orsakar långvarig infektion och kan orsaka vävnadsskada.

Det finns olika typer av DCs i tarmen som är specialiserade på att aktivera T celler till att utvecklas till exempelvis Th1 eller Th2 celler. De två huvudgrupperna av DCs som återfinns i tarmens slemhinna är IRF4- och IRF8-beroende DCs, vilka har
skilda funktioner. För att dessa DCs ska utvecklas normalt från outvecklade blodceller och reagera med optimal funktion är de beroende av genuttrycket av IRF4 respektive IRF8. Våra studier syftar till att bestämma vilken typ av DC, IRF4- eller IRF8-beroende, som behövs under utvecklingen av Th1- och Th2-svar under infektion med T. muris.

Under experimenten har vi använt oss av möss som saknar IRF4- och/eller IRF8-beroende DCs. Genom att undersöka vilka immunsvaret mössen utvecklade efter infektion med T. muris i avsaknad av en viss typ av DC har vi visat att IRF8-beroende DCs krävs för aktivering av Th1 celler, medans IRF4-beroende DCs är helt nödvändiga för aktivering av Th2 celler. När vi undersökte infekterade möss som saknade både IRF4- och IRF8-beroende DCs fann vi att dessa blev resistent och uppvisade ett Th2-svar, precis som de möss som endast saknade IRF8-beroende DCs. Dessa resultat tyder, överraskande nog, på att de möss som saknar IRF4-DCs i själva verket har förmåga att utveckla ett Th2 svar i de fall då de samtidigt saknar IRF8-DCs.

Sammanfattningsvis har vi i dessa studier studerat aktiveringen av adaptiva immunsvaret under parasitinfektion i tarmens slemhinna och identifierat de DCs som är viktiga för aktivering av Th1- och Th2-svar. En ökad förståelse kring hur dessa processer regleras är viktig för att hitta nya metoder för behandling av såväl tarmsjukdomar som allergier och andra autoimmuna sjukdomar. Förståelsen kring hur immunförsvaret regleras vid parasitinfektion kan vidare understödja nya strategier för vaccinering mot denna typ av vitt utbredda infektioner.
Acknowledgements


A big thanks to you Bill, for being a source of inspiration - your passion and immense knowledge in the DC field is remarkable and inspiring! Your challenging questions during group meetings were always for the better in the end, thank you for those!

Daniel, du har varit en klippa sedan tidens början för 5 år sen och jag hade inte kunnat haft en bättre kontorskompis än dig! Du har inte bara gett mig skrattkramper på regelbunden basis utan också alltid haft oändligt tålamod för mina jobbiga frågor som newbie på labbet. Du kommer alltid att vara en av oss i tjejgänget och alltid kommer jag minnas våra roliga stunder på labbet såväl som utanför. Thanks also Selene, for introducing me to flow cytometry (although that first compensation panel was a bit mean) and the after works at Bishops. Henrietta, tack för alla roliga stunder på labbet och utanför, efter en lång tids avsaknad av en labbgranne var det verkligen härligt när du dök upp med din härliga personlighet! 😊

Aymeric och Thorsten, hur ska jag kunna tacka er för alla oändliga svar och referenser ni försett mig med och alla de inspirerande och intressanta diskussioner vi haft! Nu slipper ni mina ”can I just ask a question” 😇! Era diskussioner har alltid lett till inspiration! Tack också för alla fina teckningar och annan konst Aymeric, du vet väl att jag nu äger en hel samling som jag tänker ställa ut på konstrundan i Österlen! Det lär blir en hel del kycklingar kan jag lova! Tack Knut för all hjälp med allt ifrån hur man hanterar en icke-fungerande PCR maskin till hur man formulerar email till djurhuspersonalen för att få snabbt svar. Din kunskap är outgrundlig och din vänlighet likaså. Lieneke, thank you for all the deep talks and for teaching me so much about histamine-rich food, thanks to you I now only drink histamine-free red wine – without even getting a stuffy nose 😇! Kasia, du härliga party-pingla med ett hjärta av guld. Vet inte om det finns någon annan som är lika bra som du på att jobba hårt och ändå bevara en sån skön attityd – det kommer jag att sakna! Du har lärt mig att vodka inte alls smakar så illa som alla säger och att en maträtt inte alls behöver smaka så illa bara för att den ser ut som det. Och just det, att en bra vän på jobbet gör livet lite roligare!
**Dora, Elsa, Una, Julia,** I will truly miss our fun girl’s nights (with Daniel).

To every past and current person in **WA/MSF group:** thank you for all the interesting discussions and all the fun after-works and retreats, this journey wouldn’t be the same without you. **Tack Christine** för ditt underbara skratt och personlighet, du borde starta din egen Youtube kanal! **Tack också Gudrun** för att du alltid hjälper till med allt möjligt!

Thank you to everyone that made **D14** such an awesome place. There are many people that I would like to thank for either lending a helping hand or just for staying on the dancefloor until the end.

**De senaste åren hade inte varit sig lika utan er,** **Robin** och **Raphaelle.** Ni har inte bara sett att mitt Champagne-intag ökat exponentiellt utan också lärt mig att man kan hitta bästa vänner för livet, även i vuxen ålder. Jag ser fram emot många Settlers-kvällar i framtiden (dock utan bråk och anklagelser, jag lovar att jag ska skärpa mig). **Ana** och **David,** ni må befinner er på aldeles för långt avstånd just nu men vår vänuskap har bara blivit starkare. (Ps. jag drömmar fortfarande om att ni ska flytta tillbaka till Sverige snart, har hört att det finns ett hus till salu precis i närheten av oss!)

**Dina** och **Roberto,** tack för alla mysiga och roliga middagar och förlåt för att vi inte kommit och hälsat på lille Elias ännu, efter den 24e kommer vi garanterat och då ska det gullas för hela slanten!

**Petra** och **Ajana,** jag hade aldrig kunnat drömma om bättre vänner som nyinflyttad 10-årig Umeå-tjej! Ni har funnits där i vått som torrt genom alla år och hjärtat värmer fortfarande när jag tänker på alla våra fina minnen. Nu när jag äntligen börjar bli klar med skrivandet lovar jag att bli bättre på att ses!

Stort tack också till familjen Persson-Bodén, **Annika, Roger, Filip, Nathalie, Staffan, Cecilia, Stig och Ulla,** för allt stöd, fina middagar och trevligt sällskap.

**Shpend** och **Ilirian,** tack för att ni båda varit de mest omtänksamma bröder man kan ha, trots att ni kunde vara ganska jobbiga småbröder och inte alltid höll våra hemligheter hemliga. Ni är de enda personerna i världen som blivit mina bästa vänner från första dagen i ert liv och kommer alltid att förbli det.


**Mami dhe babi,** falëminderit për gjithë ato të mirat që më keni jap, veçanërisht për kuriozitet që me japni. Nuk mund ta kompensoj për krejt ato të mirat por do të mundohna.
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IRF8 Transcription-Factor-Dependent Classical Dendritic Cells Are Essential for Intestinal T Cell Homeostasis

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INTRODUCTION

The intestinal mucosa contains a diverse array of T cells that play an essential role in maintaining tissue homeostasis, protection from mucosal pathogens and, when inadequately controlled, in driving immune pathology. Deciphering the key cellular and molecular pathways regulating the differentiation and maintenance of intestinal T cell subsets is thus essential to our understanding of mucosal immune homeostasis and disease and for the generation of more effective vaccines.

Intestinal T cells are diffusely distributed throughout the intestinal lamina propria (LP) and epithelium and collectively make up the largest populations of T cells in the body (Cheroutre and Madakamutil, 2004; Mowat and Agace, 2014). LP T cells consist primarily of CD4+ T cells, which enter the intestine following activation in secondary lymphoid organs and might reside within the LP for long periods of time as tissue-resident memory (Trm) cells (Turner and Farber, 2014). They are functionally heterogeneous and include distinct subsets of interleukin-17 (IL-17)-producing T helper 17 (Th17) cells, interferon-γ (IFN-γ)-producing T helper 1 (Th1) cells, and diverse populations of regulatory T cells (Tregs) (Mowat and Agace, 2014). In contrast, small intestinal (SI) intraepithelial lymphocytes (IEL) can be broadly divided into two groups; “unconventional” CD8αα+ TCRgd+ and CD8αβ+ T cells; the latter requiring β8 integrin expression by migratory IRF8 dependent CD103+CD11b+ DCs. SI homing receptor induction was impaired during T cell priming in mesenteric lymph nodes (MLN), which correlated with a reduction in aldehyde dehydrogenase activity by SI-derived MLN DCs, and inefficient T cell localization to the SI. These mice also lacked intestinal T helper 1 (Th1) cells, and failed to support Th1 cell differentiation in MLN and mount Th1 cell responses to Trichuris muris infection. Collectively these results highlight multiple non-redundant roles for IRF8 dependent DCs in the maintenance of intestinal T cell homeostasis.

SUMMARY

The role of dendritic cells (DCs) in intestinal immune homeostasis remains incompletely defined. Here we show that mice lacking IRF8 transcription-factor-dependent DCs had reduced numbers of T cells in the small intestine (SI), but not large intestine (LI), including an almost complete absence of SI CD8ββ+ and CD4+CD8αα+ T cells; the latter requiring β8 integrin expression by migratory IRF8 dependent CD103+CD11b+ DCs. SI homing receptor induction was impaired during T cell priming in mesenteric lymph nodes (MLN), which correlated with a reduction in aldehyde dehydrogenase activity by SI-derived MLN DCs, and inefficient T cell localization to the SI. These mice also lacked intestinal T helper 1 (Th1) cells, and failed to support Th1 cell differentiation in MLN and mount Th1 cell responses to Trichuris muris infection. Collectively these results highlight multiple non-redundant roles for IRF8 dependent DCs in the maintenance of intestinal T cell homeostasis.

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http://dx.doi.org/10.1016/j.immuni.2016.02.008
(Edelson et al., 2010), and an IRF4- and Notch2-dependent subset of CD103+CD11b+ DCs (Lewis et al., 2011; Persson et al., 2013). We, and others, have recently demonstrated that IRF4-dependent DCs have a non-redundant role in driving mucosal Th17 cell and Th2 cell responses (Gao et al., 2013; Persson et al., 2013; Schützer et al., 2013). In contrast, although IRF4-dependent DCs are recognized for their capacity to cross-present antigen (Shortman and Heath, 2010), and more recently to serve as a platform for CD4+ T cell dependent CD8+ T cell responses (Eickhoff et al., 2015; Hor et al., 2015), their role in the regulation of intestinal T cell homeostasis remains unknown.

**RESULTS**

**IRF8 Deletion in CD11c+ Cells Leads to a Loss in LN Resident CD8s+ and Intestinal CD103+CD11b+ DCs**

To explore the role of IRF8-dependent DCs in intestinal homeostasis, we initially assessed IRF8 expression in intestinal DC subsets by intracellular flow cytometry analysis. In the SI-LP, IRF8 was expressed by CD103+CD11b+ DCs and a minor subset of CD103- DCs (Figure 1A). In the MLN, IRF8 was expressed by lymph node resident CD8α+ MHCIIm cells (Figures 1A and 1B) and SI-PL derived CD103+CD11b+ MHCIIs cells (Figures 1A and 1B). MLN resident CD8α+ MHCIIm cells and SI-PL derived CD103-CD11b+ DCs were not observed in the SI-PL. The proportion of IRF8+ DCs in the SI-PL was lower than in the SI-LP, where IRF8 expression was downregulated upon emigration from the intestine. To assess the role of IRF8 in intestinal DC homeostasis, we crossed itgα+cre mice (Caton et al., 2007) with Irf8fl/fl mice. Germine deletion of Irf8 occurred in a small proportion of offspring and we thus tracked the presence of the deleted and floxed Irf8 allele in all pups. Quantitative genotyping and further analysis of the Irf8 locus in these mice can be found in Supplemental Information and Figures S1A and S1B. IRF8 protein was not detected in CD11c+MHCIIm splenic or MLN cells from itgα+cre.Irf8fl/fl and itgα+cre.Irf8fl/+ mice (Figure S1C and data not shown) consistent with efficient removal of the flox Irf8 allele in these cells (Figure S1B). Because itgα+cre.Irf8fl/+ mice lacked CD103+CD11b+ DCs in the SI-PL, SI-LP, and MLN, while the numbers of SI-PL and SI-LP CD103+ and SI-LP CD103- CD11b+ DCs were similar to those observed in Irf8fl/fl mice (Figures 1C–1F, Figures S2A and S2B), consistent with previous findings in IRF8-deficient mice (Alberti et al., 2003), itgα+cre.Irf8fl/fl or fl/+ mice lacked resident CD8α+ DCs in Peyer’s patch (PP), MLN, and the spleen (Figures 1G and 1H, and Figures S2C and S2D); these tissues also had enhanced numbers of resident CD11b+ DCs (Figure 1I, and Figure S2D). As recently observed in Irf8−/− mice (Grajales-Reyes et al., 2015), Irf8fl/+ and itgα+cre.Irf8−/− mice showed a major reduction in LN resident CD8α+ DCs (Figures S2E and S2F), with unaltered numbers of migratory CD103+CD11b+ DCs (Figures S2E and S2F), indicating differential gene dosage requirements between these populations.

IRF8-deficient mice have reduced numbers of circulating Ly6C+ monocytes (Kurotaki et al., 2013), which can act as precursors of intestinal macrophages (Bain et al., 2014), and increased numbers of circulating neutrophils (Holschke et al., 1996). We thus assessed whether IRF8 expression and numbers of these cells was altered in itgα+cre.Irf8fl/fl mice. IRF8 was expressed in SI-LP CD64+CD11b+ cells and circulating Ly6C+ monocytes, but not in neutrophils (Figures 11 and 1K, Figure S1C), and in itgα+cre.Irf8fl/+ mice IRF8 was deleted in SI-LP CD64+CD11b+ cells expressing the highest amounts of CD11c but not in Ly6C+ monocytes (Figures 11 and 1K). The number of SI-LP CD64+CD11b+ cells was reduced in itgα+cre.Irf8fl/+ or fl/+ mice compared with Irf8−/− mice; however, the proportion of circulating Ly6C+ monocytes and neutrophils was unchanged (Figures 1J and 1L). While the total number of splenic CD64+ and CD64+F4/80+ myeloid cells was unaltered in itgα+cre.Irf8fl/+ or fl/+ mice (Figures S2G and S2H), there was a slight yet significant increase in splenic CD64+CD11b+ cells compared with Irf8−/− mice (Figure S2H).

While IRF8 is expressed by and required for the development of plasmacytoid DCs (pDCs) (Schiavo et al., 2002), the total number of pDCs was increased in the MLN and spleen of itgα+cre.Irf8fl/+ or fl/+ mice compared with Irf8−/− mice (Figures 1M and 1N, and Figure S2I) despite an absence of IRF8 expression (Figure 1O). CD11c enriched splenic cells from itgα+cre.Irf8−/− mice failed to produce IFNs after stimulation with D-type CpG-oligodeoxynucleotide 1585 (Figure 1P), a response that is pDC dependent (Kumagai et al., 2007) and absent in itgα+cre.Tcfa−/− mice that display reduced numbers of pDCs (Claise et al., 2008) (Figure 1P). Thus IRF8 is required for the regulation of pDC homeostasis and function.

**itgα+cre.Irf8fl/+ or fl/+ Mice Have Reduced Numbers of SI-IEL**

Next we assessed the impact of IRF8 deficiency in CD11c+ cells on the composition and number of SI-IEL (Figure 2). The total number of CD45+ cells was dramatically reduced in the SI epithelium of
Figure 2. Itgax-cre.Irf8<sup>fl/fl</sup> or<sup>fl/–</sup> Mice Have Reduced Numbers of Conventional SI-IEL

(A–E) (A) Total number of CD45<sup>+</sup> cells IEL, (B) and (D) representative flow cytometry plots and (C) proportion of CD8<sup>ab</sup>+TCR<sup>b</sup>+ and CD8<sup>aa</sup>+TCR<sup>b</sup>+ among total CD45<sup>+</sup> SI-IELs in indicated mouse strains.

(F) Proportion of granzyme A+ cells in indicated SI-IEL populations.

(G) Representative immunohistochemical staining of jejunum sections from indicated mice. DAPI, blue; TCR<sup>gd</sup>, green; CD8<sup>b</sup>, red. Scale bar represents 50 μm.

(H) Percentage of CD8<sup>ab</sup>+IEL within the indicated BM derived population in single and mixed BM chimeras.

(legend continued on next page)
Itgax-cre.Irf8\textsuperscript{fl/fl} or \textsuperscript{fl/-} mice were used for experiments unless otherwise noted. Data are shown as mean ± SEM and were analyzed by unpaired Student’s t test. n.s., not significant. See also Figure S3.

**Figure 2.** Complementation between Irf8 and Irf4 is seen in T cells. Mice were intraperitoneally injected with heat-killed MEFs expressing truncated non-secreted OVA (OVA-MEF, (Sancho et al., 2009)), and OT-I cell proliferation was assessed in the MLN and spleen 3 days later by flow cytometry. Given the marked reduction of CD8\textsuperscript{+} T cell responses to soluble OVA or OVA-MEF was markedly reduced in Itgax-cre.Irf8\textsuperscript{fl/fl} or \textsuperscript{fl/-} mice compared to Itgax-cre.Irf8\textsuperscript{+/+} mice (Figures S4A and S4B). Consistent with these findings, while endogenous CD8\textsuperscript{+} T cell numbers were unaffected in the MLN, or marginally lower in the spleen of Itgax-cre.Irf8\textsuperscript{fl/fl} or \textsuperscript{fl/-} mice, effector (CD62L+CD44+) CD8\textsuperscript{+} T cell numbers were markedly reduced in both locations (Figure S4C). In contrast the total number of endogenous CD4\textsuperscript{+} T cells in the MLN and spleen as well as the number of effector CD4\textsuperscript{+} T cells in the MLN did not differ between Itgax-cre.Irf8\textsuperscript{fl/fl} or \textsuperscript{fl/-} and Irf8\textsuperscript{+/+} mice (Figure S4C). Thus Irf8-dependent DCs play a non-redundant role in cross-presenting i.p. injected cell-associated and soluble antigen to CD8\textsuperscript{+} T cells in vivo.

**T Cells Primed in Intestinal Inductive Sites of Itgax-cre.Irf8\textsuperscript{fl/fl} or \textsuperscript{fl/-} Mice Have a Reduced Capacity to Localize to the Small Intestine**

While a reduced cross-presenting capacity of Itgax-cre.Irf8\textsuperscript{fl/fl} mice could in part underlie the dramatic reduction in CD8\textsuperscript{+} T cells in the SI epithelium and LP (Figure 3A), CD8\textsuperscript{+} T cell numbers were similar in the LI-LP and lung of Itgax-cre.Irf8\textsuperscript{fl/fl} or \textsuperscript{fl/-} and Irf8\textsuperscript{+/+} mice (Figure 3A). Moreover, CD4\textsuperscript{+} T cell numbers were reduced in the SI (Figure 2C and Figure 3A) but not LI-LP or lung of Itgax-cre.Irf8\textsuperscript{fl/fl} or \textsuperscript{fl/-} mice (Figure 3A and Figure S4Q), indicating potential tissue specific defects regulating T cell accumulation in the SI. We therefore assessed the capacity of Itgax-cre.Irf8\textsuperscript{fl/fl} or \textsuperscript{fl/-} mice to support T cell priming after oral antigen administration and the subsequent migration of these cells to the SI. Briefly, VCT labeled OVA-specific CD8\textsuperscript{+} T cells were injected intravaneously (i.v.) into Itgax-cre.Irf8\textsuperscript{fl/fl} or \textsuperscript{fl/-} and Irf8\textsuperscript{+/+} mice, recipient mice were immunized intraperitoneally (i.p.) with OVA or heat treated H\textsuperscript{2}\textsuperscript{b/m1} MEFs expressing truncated non-secreted OVA (OVA-MEF, (Sancho et al., 2009)), and OT-I cell proliferation was assessed in the MLN and spleen 3 days later by flow cytometry. Given the marked reduction of CD8\textsuperscript{+} T cell responses to soluble OVA or OVA-MEF was markedly reduced in Itgax-cre.Irf8\textsuperscript{fl/fl} or \textsuperscript{fl/-} mice compared to Itgax-cre.Irf8\textsuperscript{+/+} mice (Figures S4A and S4B). Consistent with these findings, while endogenous CD8\textsuperscript{+} T cell numbers were unaffected in the MLN, or marginally lower in the spleen of Itgax-cre.Irf8\textsuperscript{fl/fl} or \textsuperscript{fl/-} mice, effector (CD62L+CD44+) CD8\textsuperscript{+} T cell numbers were markedly reduced in both locations (Figure S4C). In contrast the total number of endogenous CD4\textsuperscript{+} T cells in the MLN and spleen as well as the number of effector CD4\textsuperscript{+} T cells in the MLN did not differ between Itgax-cre.Irf8\textsuperscript{fl/fl} or \textsuperscript{fl/-} and Irf8\textsuperscript{+/+} mice (Figure S4C). Thus Irf8-dependent DCs play a non-redundant role in cross-presenting i.p. injected cell-associated and soluble antigen to CD8\textsuperscript{+} T cells in vivo.

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mice following oral administration of OVA and R848 (Figure 3C). OT-II cells proliferated equivalently well in Itgax-cre.Irf8fl/fl or fl– and Irf8fl/+ mice in response to oral administration of OVA or OVA and R848 (Figures 3D and 3E). To assess whether effector T cells primed in Itgax-cre.Irf8fl/fl or fl– mice were capable of localizing to the SI, we immunized OT-I or OT-II cell recipients orally with OVA and R848 (conditions of equal T cell proliferation) in the absence of FTY720 and their localization to the SI epithelium and LP assessed 4 days later by flow cytometry. OT-I cells primed in Itgax-cre.Irf8fl/fl or fl– mice displayed a reduced ability to mobilize to the SI but not lung or spleen (Figures 3F and 3G) although this was only significant for the SI-epithelium (Figure 3G). OT-II numbers in general were low in the epithelium, consistent with the fact that most SI-IEL are CD8+ T cells, however their accumulation in the SI-LP but not lung or spleen was significantly reduced in Itgax-cre.Irf8fl/fl or fl– compared with Irf8fl/fl mice (Figure 3G).

T Cells Primed in the MLN of Itgax-cre.Irf8fl/fl or fl– Mice Have Reduced CCR9 Expression
We hypothesized that Itgax-cre.Irf8fl/fl or fl– mice might differ in their expression of the T cell homing receptor ligands CCL25 and MadCAM-1 in the SI, or that T cells primed in the MLN of these mice might be deficient in their expression of the SI homing receptors, CCR9 and α4β7 (Agace, 2008). The proportion of CD31+ PDPN vascular endothelial cells expressing MadCAM-1 and the amount of Ccl25 mRNA in the SI of Itgax-cre.Irf8fl/fl or fl– mice were similar to that of Irf8fl/fl mice (Figures S6A and S5B) arguing against alterations in homing receptor ligand expression as a cause for reduced T cell localization to this site. To assess SI homing receptor induction, we determined CCR9 and α4β7 expression on OT-I and OT-II cells in the MLN 3 and 4 days after oral gavage with OVA or OVA and R848 and i.p. injection of FTY720 (Figure 4). In both situations, the proportion of OT-I and OT-II cells expressing CCR9, and the amount of CCR9 on CCR9-expressing cells was reduced in the MLN of Itgax-cre.Irf8fl/fl or fl– compared with Irf8fl/fl mice (Figures 4A and 4B). The amount of α4β7 on α4β7 expressing cells was also reduced, although to a lesser extent (Figure 4C).

Induction of CCR9 and α4β7 on T cells in vitro requires the vitamin A metabolite retinoic acid (RA) (Iwata et al., 2009; Svensson et al., 2008) and vitamin-A-deficient mice fail to support the generation of CCR9α4β7CD8+ T cells in MLN in vivo (Jaenson-Gyllenbaek et al., 2011). Consistent with this reflecting a T cell intrinsic requirement for RA, CCR9 and α4β7 were not induced after oral administration of OVA and R848 on adoptively transferred OT-I or OT-II cells that expressed a dominant negative form of the retinoic acid receptor x (RARα) (OT-I.Cd4-cre.dnRara+/−WT or OT-II.Cd4-cre.dnRara+/−Wt) (Pino-Lagos et al., 2011) (Figure 4D). We thus hypothesized that T cells primed in the MLN of Itgax-cre.Irf8fl/fl or fl– received less RA. Consistent with this possibility OT-I cells sorted from the MLN of recipient mice 3 days after oral OVA and R848 administration expressed lower amounts of the RA target gene P2x7r (Heiss et al., 2008) as well as Ccr9 (Figure 4E).

The generation of CCR9α4β7 T cells by intestinal DCs in vitro requires the activity of retinaldehyde dehydrogenases that convert retinal to retinoic acid (Iwata et al., 2004). We found that SI-LP derived CD103+CD11b+ DCs were significantly enriched in the fraction of MLN DCs displaying the highest aldehyde dehydrogenase (ALDH) activity (Yokota et al., 2009) (Figure 4F) and that MHCII+ MLN DCs in Itgax-cre.Irf8fl/fl or fl– mice displayed significantly reduced ALDH activity compared with Irf8fl/fl mice (Figure 4G). Collectively, these results suggest that RA production by Irf8-dependent CD103+CD11b+ migratory DCs is important for the optimal generation of SI homing T cells.

*Itgax-cre.Irf8fl/fl or fl– Mice Lack CD4+CD8α+ IEL*
Within the SI a subset of CD4+ TCRβ+ T cells differentiate into CD4+CD8α+ IEL (Morrissey et al., 1995; Reimann and Rudophi, 1995), a transition that is associated with induction of the cytotoxic T lymphocyte (CTL) associated runt-related transcription factor 3 (Runx3), and acquisition of MHC II restricted CTL like activity (Mucida et al., 2013; Reis et al., 2013). In addition to a reduction in total SI CD4+TCRβ+ IEL (Figure 2C and Figure SSA), the CD4+TCRβ+ IEL commitment of Itgax-cre.Irf8fl/fl or fl– mice lacked CD4+CD8α+ IEL (Figure 5A), expressing granzyme A (Figure 5B), and the NK and memory CD8+ T cell marker CD244 (2B4) (Figure 5C) (Mucida et al., 2013). Among total SI CD4+TCRβ+ IEL both CD4+CD8α+ and, to a lesser extent, CD4+CD8α– IEL express CD103 (Figure 5D) (Reis et al., 2013); however, all CD4+TCRβ+ IEL lacked CD103 expression in Itgax-cre.Irf8fl/fl or fl– mice (Figure 5E). The percentage of CD8α+ TCRβ+, CD8α+ TCRβ–, and CD8α– TCRβ– IEL expressing CD103, as well as the amount of CD103 expression by CD8+CD103+ IEL, were also significantly reduced in Itgax-cre.Irf8fl/fl or fl– mice (Figure 5F and data not shown). Consistent with a lack of CD4+CD8α– IEL, remaining CD4+ TCRβ+ IEL in Itgax-cre.Irf8fl/fl or fl– mice expressed lower amounts of Cd8a, Cd244, Gzma, Gzmb, and Itgax mRNA, as well as Runx3 and Tbx21 (encoding Tbet) (Figure 5G), a transcription factor associated with the transition of CD4+ T cells into CD4+CD8α+ IEL (Mucida et al., 2013; Reis et al., 2013). Lack of CD4+CD8α– IEL and reduced CD103 expression by CD4+TCRβ+ IEL was T cell extrinsic as CD4+CD8α+ IEL and CD103 expressing CD4+TCRβ+ IEL were generated efficiently from Itgax-cre.Irf8fl/fl BM in WT (CD45.1)+Itgax-cre.Irf8fl/fl (CD45.2) as well as Rag1–/–Itgax-cre.Irf8fl/fl mixed BM chimeras (Figure 5H, data not shown). Further, CD4+CD8α– IEL and CD103 expressing CD4+TCRβ+ IEL deriving from Itgax-cre.Irf8fl/fl BM were readily...
Figure 4. T Cells Primed in the MLN of Itgax-cre.Irf8\textsuperscript{lox/lox} or Irf8\textsuperscript{−/−} Mice Have Reduced Expression of Small Intestinal Homing Receptors
(A) Representative flow cytometry plots and (B) pooled data of (A) and (B) CCR9 and (C) α4β7 expression on OT-I or OT-II cells in the MLN of indicated recipient mice 3 (OT-I) or 4 (OT-II) days after oral gavage with OVA or OVA and R848.

Immunity 44, 1–15, April 19, 2016

Please cite this article in press as: Luda et al., IRF8 Transcription-Factor-Dependent Classical Dendritic Cells Are Essential for Intestinal T Cell Homeostasis, Immunity (2016), http://dx.doi.org/10.1016/j.immuni.2016.02.008
detected in Ccr2−/− (CD45.1+):Itgax-cre.Irf8fl/fl (CD45.2+) mixed BM chimeras (Figure 5I) and were present in normal numbers in Itgax-cre.Tcf4fl/fl mice (Figure S4F).

β8 Integrin Subunit Expression by IRF8-Dependent CD103+CD11b+ DCs Is Required for the Generation of CD4+CD8αα IEL

Because the differentiation of CD4+ TCRββ T cells to CD4+ CD8αα IEL and the induction of CD103 on intestinal IEL is TGF-β dependent (El-Asady et al., 2005; Reis et al., 2013), we next assessed the expression of genes involved in TGF-β production and activation in intestinal DC subsets. qPCR analysis demonstrated that Itg8b, encoding the β8 integrin chain involved in the activation of latent TGF-β (Travis and Sheppard, 2014), was expressed selectively by CD103+CD11b+ DCs (Figure 5J).

To investigate the functional significance of β8 integrin expression by CD103+CD11b+ DCs in CD4+CD8αα IEL development, we generated Itgax-cre.Itg8bfl/fl mice. While displaying normal numbers of CD45+ SI-IEL and proportions of CD4+TCRββ SI-IEL (Figure 5K, data not shown), these animals had significantly reduced proportions of CD4+CD8αα IEL compared with Itg8bfl/fl littermates (Figure 5K, data not shown). Further BM from Itg8bfl/fl, but not from Itgax-cre.Itg8bfl/fl mice rescued the generation of CD4+CD8αα SI-IEL and CD103 expression on CD4+ TCRββ SI-IEL in mixed BM chimeras with Itgax-cre.Irf8fl/fl BM (Figure 5L). Thus β8 integrin expression by IRF8-dependent DCs is required for the generation of CD4+CD8αα IEL.

Itgax-cre.Irf8fl/fl or fl/− Mice Lack Intestinal Th1 Cells

We next compared intestinal LP CD4+ T cell subset composition in Itgax-cre.Irf8fl/fl or fl/− and Irf8fl/fl mice (Figures 6A and 6B). Strikingly, IFN-γ–IL-17+ CD4+ T cells were almost absent and IFN-γ–IL-17+ CD4+ T cells were reduced in the SI-LP and LI-LP of Itgax-cre.Irf8fl/fl or fl/− mice (Figures 6A and 6B). In contrast, Itgax-cre.Irf8fl/fl or fl/− mice had elevated proportions of intestinal IL-17+ cells, while the proportions of Foxp3+CD4+ T cells were slightly reduced in the LI but not SI (Figures 6A and 6B). Consistent with these findings, SI-LP CD4+ T cells from Itgax-cre.Irf8fl/fl or fl/− mice expressed lower amounts of Tbx21, but not Rorc or Foxp3, compared with Irf8fl/fl mice (Figures 6C). Naïve splenic CD4+ T cells from Itgax-cre.Irf8fl/fl and Irf8fl/fl mice differentiated equally well into IFN-γ producing Th1 cells in vitro (Figure 6D), and IFN-γ producing CD4+ T cells deriving from Itgax-cre.Irf8fl/fl BM were present in the SI and MLN of WT (CD45.1+):Itgax-cre.Irf8fl/fl (CD45.2+) mixed BM chimeras (Figure 6E). Further, IFN-γ–producing SI-LP CD4+ T cells were readily detected in Itgax-cre.Tcf4fl/fl mice (Figure 6F). Despite these defects in mucosal T cell homeostasis, the composition of the cecal and colonic microbiota, including amounts of segmented filamentous bacteria, did not differ between Itgax-cre.Irf8fl/fl or fl/− and Irf8fl/fl mice (Figures S6A–S6D), and Itgax-cre.Irf8fl/fl or fl/− mice displayed no major defects in intestinal barrier function as assessed by amounts of serum endotoxin (Figure S6E).

Th1 Cell Differentiation Is Impaired in the MLN of Itgax-cre.Irf8fl/fl or fl/− Mice

To assess whether Th1 cell priming in MLN was altered in Itgax-cre.Irf8fl/fl or fl/− mice, OT-II cells were injected i.v. into Itgax-cre.Irf8fl/fl or fl/− and Irf8fl/fl mice and recipients were immunized with OVA, LPS, and sCD40 i.p., a protocol previously demonstrated to generate both IFN-γ and IL-17 producing OT-II populations (Persson et al., 2013). While OT-II cells primed in the MLN of both Itgax-cre.Irf8fl/fl or fl/− and Irf8fl/fl mice expressed IL-17 (Figures 7A and 7B), the MLN of Itgax-cre.Irf8fl/fl or fl/− mice failed to support Th1 cell differentiation (Figures 7A and 7B). Ccr2−/− mice, that displayed dramatically reduced numbers of CD4+CD11b+ cells in the MLN 4 days after immunization (Figure 7C), supported efficient Th1 cell differentiation (Figure 7D), as did Itgax-cre.Tcf4fl/fl mice (Figure 7E). Finally, when Itgax-cre.Irf8fl/fl or fl/− and Irf8fl/fl mice were infected orally with 20 Trichuris muris (T. muris) eggs, a dose that drives a Th1 cell response resulting in chronic infection in C57BL/6 mice (Bancroft et al., 1994), chronic infection developed in Irf8fl/fl mice but not Itgax-cre.Irf8fl/fl or fl/− mice (Figure 7F). Further while both sets of mice generated an equivalent T. muris specific immunoglobulin G1 (IgG1) response, Itgax-cre.Irf8fl/fl or fl/− mice failed to mount a T. muris-specific IgG2c response (Figure 7G). Collectively, these findings suggest a role for IRF8-dependent DCs in the generation of intestinal Th1 cell responses and offer one likely mechanism underlying the dramatic reduction in Th1 cells in the SI-LP and LI-LP of Itgax-cre.Irf8fl/fl or fl/− mice.

DISCUSSION

Itgax-cre.Irf8fl/fl or fl/− mice displayed a similar reduction in classical DC subsets to that previously reported in Irf8−/− and Irf82D24C mice (Alberti et al., 2003; Edelson et al., 2010). However, in contrast to Irf8-deficient mice that lack pDCs (Schiavoni et al., 2002), Itgax-cre.Irf8fl/fl or fl/− mice had increased numbers of pDCs, although these appeared dysfunctional. Irf82D24C mice have also been reported to have higher numbers of pDCs (Tailer et al., 2008), collectively indicating that distinct IRF8 interacting partners might be required for pDC development versus pDC homeostasis and functionality. Although it remains possible that dysfunctional IRF8-deficient pDCs influence SI T cell homeostasis, our findings provide evidence that it is primarily an absence of classical IRF8-dependent DCs that underlie the defects in intestinal T cell homeostasis observed in Itgax-cre.Irf8fl/fl or fl/− mice.
Please cite this article in press as: Luda et al., IRF8 Transcription-Factor-Dependent Classical Dendritic Cells Are Essential for Intestinal T Cell Homeostasis, Immunity (2016), http://dx.doi.org/10.1016/j.immuni.2016.02.008

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Our finding that Irf8−/− mice had normal numbers of SI CD8αβ+ T cells, despite a major reduction in LN resident CD8α+ DCs, suggests that a lack of migratory CD103+CD11b+ DCs is responsible for the paucity of SI CD8αβ+ T cells in Itgax-cre.Irf8−/− or v/v− mice. One likely contributing factor underlying this deficiency is the reduced capacity of Itgax-cre.Irf8+/+ or v+/v+ mice to cross-present antigen. Nevertheless, these mice had similar numbers of CD8αβ+ T cells as controls in the LI and lung, indicating additional tissue specific mechanisms. In this regard, both CD4+ and CD8+ T cells primed in the MLN of Itgax-cre.Irf8+/+ or v+/v+ mice had reduced expression of the SI homing receptor CCR9 and localized less efficiently to the SI but not lung. Although both SI-derived CD103+CD11b+ and CD103−CD11b+ DCs display retinaldehyde dehydrogenase activity (Cericovici et al., 2013; Denning et al., 2011; Persson et al., 2013), we show here that the absence of IRF8DCs display the highest amounts of aldehyde dehydrogenase activity in MLN, and their absence in itgax-cre.Irf8−/− or v−/− mice resulted in a decrease in DC-derived aldehyde dehydrogenase activity. We thus hypothesize that optimal generation of “SI tropic” T cells requires RA signals from CD103+CD11b+ DCs, potentially providing an additional explanation for the reduced numbers of SI CD8αβ+ and SI CD4+ T cells in Itgax-cre.Irf8−/− or v−/− mice. These results do not exclude the possibility that SI-derived CD103+CD11b+ DCs also support “SI tropic” T cell generation in the MLN through additional mechanisms. Notably, SI lymphoid tissues were also recently suggested to be sites of unconventional IEL precursor activation, associated with an enhanced expression of CCR9 and α4β7 (Guy-Grand et al., 2013). Whether a similar mechanism contributes to the reduction in unconventional IEL numbers or whether the development and maintenance of these cells is altered in itgax-cre.Irf8−/− or v−/− mice awaits further analysis.

In addition to an overall reduction in SI CD4+ T cell numbers CD4+ IEL of Itgax-cre.Irf8+/+ or v+/v+ mice failed to express CD103 and to differentiate into CD4+CD8α+ IEL. These results are consistent with a recent study in Batf3−/− mice indicating an important role for cell adhesion molecule 1 (Cad1m) expression by Batf3 dependent DCs in driving CD4+CD8α+ IEL generation (Cortez et al., 2014). Here we show that αvβ8 integrin expression by CD103+CD11b+ DCs also plays a key role in the generation of CD4+CD8α+ IEL as well as in the induction of CD4+CD8α+ IEL. Whether αvβ8 and Cad1m function together or independently of one another to promote CD4+CD8α+ IEL development remains to be determined.

Itgax-cre.Irf8−/− or v−/− mice had normal proportions of intestinal FoxP3+ Treg cells, consistent with previous findings in Batf3−/− mice (Edelson et al., 2010) and increased proportions of intestinal IL-17+IFN-γ− Th17 cells. This phenotype is markedly distinct from that of itgax-cre.Igb8−/− mice that have reduced numbers of colonic FoxP3+ T cells and Th17 cells (Melton et al., 2010; Travis et al., 2007) suggesting that αvβ8 expression by a CD11c+ cell distinct from IRF8-dependent DCs is required for intestinal Th17 cell homeostasis. Alternatively a complete absence of IRF8-dependent DCs might lead to the generation of additional αvβ8 independent signals that promote the generation of these cells. Given our previous work demonstrating reduced numbers of intestinal IL-17+IFN-γ− Th17 cells in itgax-cre.Irf8+/+ or v+/v+ mice (Persson et al., 2013), we speculate that the increase in Th17 cells observed in itgax-cre.Irf8−/− or v−/− mice is due to the absence of SI-derived migratory intestinal DCs, as well as to the defect in IFN-γ production by IL-17+ cells.

In contrast to the moderate changes in intestinal Th17 cell composition, intestinal Th1 cells were absent and IFN-γ−IL-17− producing CD4+ T cells severely reduced in both the SI and colon of itgax-cre.Irf8+/+ or v+/v+ mice. Consistent with these findings Batf3−/− mice appear to display reduced numbers of MLN Th1 cells in steady state (Everts et al., 2016), although intestinal IFN-γ−producing Th1 cells have been observed in these mice (Welty et al., 2013). Although the reason for this discrepancy remains to be determined, Batf3−/− mice can develop IRF8-dependent DCs in settings of elevated IL-12 (Tussworath et al., 2012) and intestinal Th1 cells might have been generated under such conditions. Alternatively, absence of IRF8 in additional CD11c+ cells might contribute to the paucity of intestinal Th1 cells in itgax-cre.Irf8−/− or v−/− mice. In contrast to intestinal derived migratory CD103+CD11b+ DCs and MLN resident DC subsets, most LP derived CD103+CD11b− DCs in the MLN constitutively produce IL-12 (Everts et al., 2016), and we here provide evidence for a role of IRF8-dependent DCs in driving Th1 cell differentiation in MLN, providing one mechanistic explanation underlying this phenotype.

In summary, our findings suggest a key role for IRF8-dependent classical DCs in multiple aspects of intestinal T cell homeostasis that are distinct from those of intestinal Notch2 and IRF4-dependent DCs, whose absence results in a selective reduction in intestinal Th17 cells (Lewis et al., 2011; Persson et al., 2013; Welty et al., 2013) and, as we demonstrate here, does not impact intestinal IEL composition. Such results have important implications not only for the design of DC targeted mucosal vaccines but also for the exploration of...
Figure 6. *Itgax-cre, Ifnγ* or *Ifnγ* Mice Fail to Mount Mucosal Th1 Cell Responses

Representative flow cytometry plots (A) and percentage (B) of Treg and cytokine producing cells within (A) and (B) SI-LP and (B) LI-LP CD4+ T cells of *Ifnγ*^fl/fl^ and *Ifnγ*^fl/fl^ or fl/– mice. (C) Relative expression of indicated transcription factors in sorted SI-LP CD4+ T cells from *Ifnγ*^fl/fl^ and *Itgax-cre, Ifnγ*^fl/fl^ or fl/– mice. (D) Representative flow cytometry plots of Tbet and IFN-γ expression by splenic CD4+ T cells from indicated mice after 4.5 days culture under Th1 cell polarizing conditions. (E) Percentage of IFN-γ+/IL17+ cells within the indicated BM derived CD4+ SI-LP (left panel) or CD4+ MLN (right panel) population in single and mixed BM chimeras. (F) Percentage of cytokine producing CD4+ T cells in the SI-LP of *Tcf4*^fl/fl^ and *Itgax-cre, Tcf4*^fl/fl^ mice. (A–E) Results are from 2–5 independent experiments or (F) from one representative experiment of two performed. Each dot represents one mouse. Error bars represent mean ± SEM. *p < 0.05, **p < 0.01, ***p < 0.001, ****p < 0.0001, ns, not significant. See also Figure S6.
DC-centric therapies in the treatment of inflammatory bowel disease.

**EXPERIMENTAL PROCEDURES**

**Mice**

Mice were bred and maintained at the Biomedical Center (BMC), Lund University, or Clinical Research Center, Malmö. Animal experiments were performed in accordance with the Lund/Malmö Animal Ethics Committee. For information on the mouse strains, see Supplemental Information.

**Cell Isolation**

SI-IEL isolation was performed as previously described (Svensson et al., 2002). The SI-LP, LI-LP cell isolation was performed as described previously (Schulz et al., 2009) with minor changes regarding used enzymes: collagenase A and VIII was replaced with Liberase TM (0.3 WuenschU/ml, Roche). For analysis of SI endothelial cells, SI-LP suspensions were stained directly after enzymatic digestion. For generation of lung cell suspensions, perfused lungs were cut into small pieces and digested for 40 min at 37°C in RPMI 1640 (GIBCO, Invitrogen) with Liberase TM (0.3 WuenschU/ml) and DNase I (30 μg/ml, Sigma Aldrich) for 40 min at 37°C while shaking and filtered prior to analysis. For DC purification, sCD11c conjugated MACS beads (Miltenyi) were used to enrich for pDC and DCs prior to cell sorting.

**Flow Cytometry**

Flow cytometry was performed according to standard procedures. Dead cells identified as propidium iodide+ by fixable Viability Dye eFluor® 450 (eBioScience), or by Red or Aqua LIVE/DEAD Fixable Dead Cell Staining Kit (Life Technologies) and cell aggregates (identified on FSC-A versus FSC-W scatterplots) were excluded from analyses. Intracellular staining was performed using the FoxP3 Fixation/Permeabilization Kit (eBioscience) according to the manufacturer’s instructions. Data were acquired on a FACSAriaII or LSRII (BD Biosciences) and analyzed using FlowJo software (Tree Star). Sorting was performed on a FACSAriaII or on a MoFlow® Astrios (Beckman Coulter).

**Adoptive Transfers**

Bone marrow (BM) chimeras were generated by i.v. injection of BM (2 × 10^6) cells into irradiated (900 rad) recipients. Analysis of BM chimeras was performed 8 weeks after cell transfer. For T cell transfers, naive OT-I or OT-II cells were labeled with CellTrace Violet (Life Technologies) according to the manufacturer’s instructions, and injected i.v. (1–3 × 10^6 cells/mouse) into recipient mice. For immunization protocols, see Supplemental Information.

**Cell Culture**

SI-LP, LI-LP, and MLN cells were re-stimulated in vitro essentially as described previously (Persson et al., 2013), except SI-LP and LI-LP were cultured in the presence of 5% CO₂ and 20% FCS.

**Figure 7. Itgax-cre.Irf8^fl/fl or fl/− Mice Fail to Prime Th1 Cells in the MLN**

(A) Representative flow cytometry plots and (B) percentage of IFN-γ and IL-17 producing OT-II cells in the MLN of indicated mice 4 days after i.p. immunization with OVA, sCD40, and LPS. (C) Total number of CD11b+CD64+ cells and (D) and (E) percentage of IFN-γ or IL-17 producing OT-II cells in the MLN of (C) and (D) Ccr2−/− and control C57BL/6 mice or (E) Tcf4−/− and itgax-cre.Tcf4−/− mice 4 days after i.p. immunization with OVA, sCD40, and LPS. (F) Worm burden and (G) amounts of E/S specific serum IgG1 and IgG2c in Irf8−/− and itgax-cre.Irf8−/− or fl/− mice 35 days after oral administration of T.muris eggs (infective dose approximately 20). (G) opened triangles represent uninfected control mice. Results are from (D) one representative experiment of two performed and (A–C, E–G) 2 independent experiments. (B–F) Each dot represents one mouse or (G) a mean value of data pooled from 7-8 mice (red and black circles) or 3 mice (opened triangles). (B–F) Error bars represent mean ± SEM or (G) ± SD. **p < 0.01, ****p < 0.0001, ns, not significant.

Please cite this article in press as: Luda et al., IRF8 Transcription-Factor-Dependent Classical Dendritic Cells Are Essential for Intestinal T Cell Homeostasis, Immunity (2016), http://dx.doi.org/10.1016/j.immuni.2016.02.008
0.25 μg/ml PMA and 0.5 μg/ml ionomycin (Sigma). For Th1 cell polarization and pDC stimulation protocols, see Supplemental Information.

Statistical Analysis
Statistical significance was estimated by using GraphPad Prism software (GraphPad), with Mann-Whitney U test or two-way ANOVA where applicable.

SUPPLEMENTAL INFORMATION
Supplemental Information includes six figures and Supplemental Experimental Procedures and can be found with this article online at http://dx.doi.org/10.1016/j.immuni.2016.02.008.

AUTHORS CONTRIBUTIONS

ACKNOWLEDGMENTS
We would like to thank Dr. A.M. Mowat (Glasgow University) for constructive comments during the preparation of this manuscript and for providing bone marrow from Ccr2−/− CD45.1 mice. Dr. D. Holmberg and T.D. Hannibal (Copenhagen and Lund University) for providing Tc4cre and Ifox3Cre.Tcf4fl/fl mice. Dr. R.J. Noelle (King’s College London) for providing CD4−/− and dnRarα−/− mice. Dr. J.E. Konkel (Manchester University) for help in IEL preparation at Manchester, Dr. C. Reis e Sousa (The Francis Crick Institute) for providing OVA-expressing H2Kb MEFs. A.-C. Selberg for animal care and genotyping, and A.N. Hansen for microbial DNA extraction. This work was supported by a Sapere Aude III senior researcher grant from the Danish Research Council, the Lundbeckfonden (grant number R15S-2014-4184), grants from the Swedish Medical Research Council, Kocks, Osterlund, Professor Nanna Svartz. Richard and Ruth Julins and the Royal Physiographic Society, and a clinical grant from the Swedish national health service.

Received: September 21, 2015
Revised: December 16, 2015
Accepted: February 9, 2016
Published: April 5, 2016

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transports apoptotic intestinal epithelial cells to T cell areas of mesenteric lymph nodes. J. Exp. Med. 191, 435–444.


Supplemental Information

IRF8 Transcription-Factor-Dependent Classical Dendritic Cells Are Essential for Intestinal T Cell Homeostasis

Figure S1. Genotypic characterization of Itgax-cre.Irf8<sup>fl/fl</sup>, Itgax-cre.Irf8<sup>fl/-</sup>, Irf8<sup>fl/fl</sup> and Irf8<sup>fl/-</sup> mice, related to Figure 1. 

(A and B) Quantitative genotyping of (A) ear biopsy and (B) sorted splenic CD11c<sup>+</sup>MHCII<sup>+</sup> DCs and CD4<sup>+</sup>TCRβ<sup>+</sup> and CD8<sup>+</sup> T cells. Delta, deleted allele. Each dot represents results from an individual mouse. Bars, mean (SEM). (C) Representative intracellular IRF8 staining in neutrophils (CD11b<sup>+</sup>Ly6G<sup>+</sup>SSC<sup>int</sup>), splenic CD11c<sup>+</sup>MHCII<sup>+</sup> DCs, and CD4<sup>+</sup>TCRβ<sup>+</sup> and CD8<sup>+</sup> TCRβ<sup>+</sup> T cells from indicated mice. Data are representative plots from 2-3 independent experiments.
Figure S2. Mononuclear phagocyte composition in Itgax-cre.Irf8<sup>fl/fl</sup> or fl/<sup>-</sup> and Irf8<sup>hap/hap</sup> mice and effect of Irf8 haplo-insufficiency on intestinal DC subset composition, related to Figure 1. (A and C) Representative flow cytometry plots and (B and D) total number of (A and B) colonic and (C and D) splenic DC subsets in indicated mice. (E and F) LN resident CD8α but not migratory CD103<sup>+</sup> CD11b<sup>+</sup> DCs are reduced in mice expressing one allele of Irf8. (E) Representative flow cytometry plots and (F) total number of MLN, PP and SI-LP DC subsets in indicated mice. (G) Representative flow cytometry plots and (H) total number of splenic myeloid subsets in indicated mice. (I) Total number of splenic pDCs in indicated mice. (A-I) Data are pooled from 2-4 independent experiments. Each dot represents one mouse. Bars, mean (± SEM). *p<0.05, ** p<0.01, ***p<0.001, ns, not significant.
Figure S3. IEL composition in \textit{Itgax-cre.Irf8}^{fl/fl} or fl/⁻, \textit{Itgax-cre.Irf4}^{fl/fl} or fl/⁻ and \textit{Itgax-cre.Tcf4}^{fl/fl} mice, related to Figure 2.  
(A) Total number of SI-IEL subsets in \textit{Irf8}^{fl/fl} and \textit{Itgax-cre.Irf8}^{fl/fl} or fl/⁻ mice. (B and D) Total number of CD45⁺ SI-IEL and (C and E) proportion of SI-IEL subsets within CD45⁺ IEL in indicated mice. (F) Proportion of CD4⁺ IEL expressing CD8α in \textit{Itgax-cre.Tcf4}^{fl/fl} mice. Results are pooled from 3-9 independent experiments. Each dot represents one mouse. Bars, mean (± SEM). ** p<0.01, ****p<0.0001, ns, not significant.
Figure S4. Itgax-cre.Irf8\textsuperscript{fl/fl} mice display defects in cross-presentation of soluble and cell associated antigen, related to Figure 3.

(A) Representative flow cytometry plots and (B) total number of OT-I cells in the MLN and spleen of Irf8\textsuperscript{fl/fl} and Itgax-cre.Irf8\textsuperscript{fl/fl} or fl/− mice 3 days after i.p. immunization with heat shocked OVA-MEF or soluble OVA. (C) Total number of CD4\textsuperscript{+} and CD8\textsuperscript{+} T cells and effector CD62L\textsuperscript{−}CD44\textsuperscript{+} T cells in the MLN and spleen of Irf8\textsuperscript{fl/fl} and Itgax-cre.Irf8\textsuperscript{fl/fl} or fl/− mice. Data are pooled from 2-5 independent experiments. Each dot represents one mouse. Bars, mean (± SEM).

*p<0.05, ** p<0.01, ***p<0.001, ns, not significant.
Figure S5. Small intestinal expression of MadCAM-1 and CCL25 is not altered in Itgax-cre.Irf8<sup>fl/fl</sup> mice, related to Figure 4. (A) Representative plots of MadCAM-1 expression on SI-LP (jejunal) vascular endothelial cells and (B) Ccl25 mRNA levels in SI (jejunal) tissue from indicated mice. Data are from 2-3 independent experiments. (B) Each dot represents one mouse. Bars, mean (± SEM). ns, not significant.
Figure S6. Colonic and cecal microbiota composition appears similar between Itgax-cre.Irf8fl/fl or fl/- and Irf8fl/fl mice, related to Figure 6.

(A-C) Microbial analysis was performed using 16S rDNA amplicon sequencing on 11 Irf8fl/fl and 17 Itgax-cre.Irf8fl/fl or fl/- 12-16 w old female mice, cohoused as littermates. (A) Alpha and beta diversity of cecal and colonic microbiota samples. Top: The median alpha diversity based on Shannon index of unfiltered microbiota data. Bottom: Median beta diversity based on Sørensen index. The upper and lower whiskers correspond to the 25th and 75th percentiles. (B) Non-metric Multi-Dimensional Scaling (NMDS) plot using Bray-Curtis dissimilarity indices. (C) Taxa summary plots at family level. “Unknown” refers to OTUs that we were unable to classify. Data represent mean relative abundance. (D) Levels of segmented filamentous bacterial (SFB) DNA in cecal and colonic samples and (E) serum endotoxin levels in Irf8fl/fl and Itgax-cre.Irf8fl/fl and fl/- mice. Each point represents an individual mouse. Bars, mean (± SEM).
Supplemental Experimental Procedures

Mice

The following mouse strains were used during the course of this study: Itgax-cre (Itgax-Cre) (Caton et al., 2007), C57BL/6-Tg(Tcra Tcrb)425Cbn/J (OT-II), C57BL/6-Tg(Tcra Tcrb)1100Mjb/J (OT-I), C57BL/6, C57BL/6 (CD45.1), C57BL/6 (CD45.1/CD45.2), B6.129S1-Itf4tm1Rdf/J (Klein et al., 2006), Tcf4\(^{fl/fl}\) (Bergqvist et al., 2000), Ccr2\(^{-/-}\) (Saederup et al., 2010), Cd4-Cre (Lee et al., 2001), dnRara\(^{ld/ld}\) (Rajaii et al., 2008) and Rag1\(^{-/-}\) mice. For generation of Itf4\(^{fl/fl}\) mice an Itf4 ES cell clone with conditional potential (clone EPD0246_7_C11, KOMP repository) was injected into blastocysts. Germ line transmitting offspring (Itf4\(^{lacZ/lacZ}\) mice) were crossed to FLPe recombinase mice to generate Itf4 conditional KO mice (Itf4\(^{fl/fl}\)). Itgax-cre, Itgb8\(^{fl/fl}\) mice (Travis et al., 2007) were maintained at the University of Manchester, UK.

Mouse genotyping

Presence of a wildtype (wt) or flox Itf4 allele was identified in ear biopsies with the following primers: itf4 fw 5’GCCCTGCTTTGAATTTCTGGCCT 3’, itf4 wt_rev 5’ACATGTGTATCCACCCTTCCTCTCC 3’, and itf4 flox_rev 5’GCACCGTCAAAGACTTTCCGCC 3’ resulting in a 370 bp band for the flox allele and a 200 bp band for the wt allele. Presence of a deleted or flox Itf4 allele was identified with the following primers; itf4 fw 5’AAAAAAAGCAGGCTGGCGCGGCGCGC 3’, itf4 flox_rev 5’GCACCGTCAAAGACTTTCCGCC 3’, itf4 delta_rev 5’CCCTTTGAACTGATGGCGAGCTC 3’ resulting in an approximate 200 bp band for the flox allele and a 170 bp band for the deleted allele.
Quantitative analysis of the \textit{Irf8} floxed and deleted allele in \textit{Itgax-cre.Irf8^{fl/fl}}, \textit{Itgax-cre.Irf8^{fl/wt}}, \textit{Irf8^{wt}} and \textit{Irf8^{fl/fl}} mice

Quantitative analysis of the \textit{Irf8} flox and deleted allele in ear biopsies or sorted cell populations was performed as previously described (Persson et al., 2013) using the flox and delta primers described above. The amount of flox or deleted (delta) allele was calculated as a delta or flox locus ratio to the reference gene locus CD45.2 (CD45.2\_fw 5’ GCCTGTATCTAAACCTGAGT 3’ and CD45.2\_rev 5’ TTCCCTAGTGGAATTTTACATTA 3’). Data was stratified by assuming that the same numbers of alleles relative to CD45.2 were present in all investigated samples. Such analysis gave the expected ratio of \textit{Irf8} flox and deleted bands in ear biopsies of \textit{Itgax-cre.Irf8^{fl/fl}}, \textit{Itgax-cre.Irf8^{fl/wt}}, \textit{Irf8^{wt}} and \textit{Irf8^{fl/fl}} mice (Figure S1A). While both alleles were detected at similar levels in cells sorted from \textit{Irf8^{wt}} mice only the \textit{Irf8} deleted allele was detected in sorted splenic DCs from \textit{Itgax-cre.Irf8^{fl/fl}} and \textit{Itgax-cre.Irf8^{fl/wt}} mice (Figure S1B). Both \textit{Irf8} flox and deleted alleles were detected in CD4^{+} and CD8^{+} splenocytes from \textit{Itgax-cre.Irf8^{fl/fl}} and \textit{Itgax-cre.Irf8^{fl/wt}} mice (Figure S1B) indicating, similar to our previous findings in \textit{Itgax-cre.Irf4^{fl/fl}} mice (Persson et al., 2013), that CD11c driven Cre recombinase can drive a degree of off target deletion of the \textit{Irf8} floxed allele in hematopoietic cells.

\textbf{Antibodies and reagents}

The following mAbs and reagents were used for during the study: anti-NK1.1 (PK 136), anti-CD19 (6D5 or 1D3), anti-CD3e (17A2 or 145-2C11), anti-MHC II(IA/I-E) (M5/114.15.2), anti-CD11b (M1/70), anti-CD8α (53-6.7), anti-Ly6C (HK1.4 or AL-21), anti-Ly6G (1A8), anti-CD45.2 (104), anti-B220 (RA3-6B2), anti-BST2 (927 or...
Preparation of OVA-MEsF for immunization

H-2\textsuperscript{bm1} MEFs expressing truncated non-secreted OVA (OVA-MEF, (Sancho et al., 2009)) were prepared as described previously (Chen et al., 2007). Briefly, harvested OVA-MEFs were suspended in PBS at a concentration 5\times10^7/ml and heat shocked for 10 min at 45°C. Treated cells were subsequently incubated for 5h at 37°C prior to immunization.

Immunizations

OT-I recipients were immunized by oral gavage with OVA (5mg, Grade V, Sigma-Aldrich) or OVA (50 mg) and R848 (20 µg, InvivoGen) or i.p. with heat shocked OVA- MEFs (10^7 cells/mouse) or OVA (0.1mg/mouse, Grade VI, Sigma-Aldrich). OT-II recipients were immunized by oral gavage with OVA (50 mg) or OVA (50 mg) and R848 (20 µg). At day 1 after immunization recipient mice were injected with
FTY720 (20 µg/mouse; Cayman) in saline i.p. OT-I recipients were sacrificed 3 days after immunization while OT-II cell recipients received an additional FTY720 injection day 3 and were sacrificed 4 day after immunization. For T cell homing experiments FTY720 was omitted and animals were sacrificed 4 days after immunization. For cytokine analysis studies OT-II cell recipients were immunized i.p. with OVA (0.5mg, Grade VI, Sigma-Aldrich), αCD40 (25 µg, BioLegend) and LPS (20 µg, Sigma-Aldrich), treated with FTY720 as above, and sacrificed 4 day after immunization.

**In vitro cultures**

For *in vitro* Th1 cell polarization, FACS-sorted naive (CD4⁺CD62L⁺CD25⁻CD44lo) T cells were cultured in αCD3-coated (clone 145-2C1, BioXCell, 5 ug/mL) round bottom 96 well plates (0.25 x10⁶ cells /ml) in the presence of αCD28 (1ug/mL, clone 37.51, Biolegend), IL-2 (20 ng/mL, bio-techne), IL-12 (20 ng/mL, bio-techne), and αIL-4 (10ug/mL clone 11B11, BioXCell) for 4.5 d prior to re-stimulation and intracellular cytokine analysis. For splenic CD11c⁺ cell cultures, MACS-enriched CD11c⁺ cells were suspended in RPMI 1640 containing with 10% FCS (Sigma Aldrich), 1 mM sodium pyruvate (Gibco), 10 mM HEPES, 100 U/ml Penicillin and 100 µg/ml Streptomycin, 50 µg/ml Gentamycin (Gibco) (R10 medium) and plated (2.5x10⁵ cells/well) in 96 well U-bottom plates in the presence/absence of CpG ODN1585 (5 µg/ml, InvivoGen) for 42 h at 37°C. IFNα levels in culture supernatants was assessed using the VeriKine™ Mouse IFNα ELISA Kit (PBL Assay science) according to manufacturers instructions.
**Real-Time PCR**

For analysis of sorted cells, total RNA was isolated from 1-1.5x10^4 sorted cells using Absolutely RNA Nanoprep Kit (Agilent) or Quick-RNA MicroPrep kit (Zymo Research). cDNA was generated and amplified using the Ovation® PicoSL WTA Systems V2 (Nugen, San Carlos, US). Quantitative PCR was performed on a MyiQ Single Color-Real-Time PCR detection System (Bio-Rad), using KAPA SYBR FAST detection reagent (Kapabiosystems). For analysis of intestinal tissues, total RNA was isolated using the RNeasy Mini Kit (Agilent). cDNA was generated using Superscript III First-Strand Kit (Invitrogen) with both random hexamers and pT-primer present and used as a template for quantitative real-time PCR. Quantitative PCR was performed on a MyiQ Single-Color Real-Time PCR Detection System, using SsoFAST EvaGreen SuperMix (Bio-Rad). The expression of all genes was normalized to the two house-keeping genes beta-actin and GAPDH.

**Immunohistochemistry**

Frozen sections (7-8 µm) of SI tissue (6-12 cm from the pylorus) were fixed and blocked with 10% donkey serum. Endogenous peroxidase and biotin activities were quenched with 0.1 % H_2O_2 (vol/vol) in PBS and Avidin-Biotin blocking kit (Vector Laboratories), respectively. TCRγδ was detected using FITC conjugated anti-TCRγδ (GL3, BD Biosciences) and the signal was amplified with Alexa-488 signal amplification kit (Molecular Probes). CD8β was detected using biotinylated anti-CD8β (clone H35-17.2, eBioscience) and signal was amplified with biotinyl-tyramide signal amplification kit (PerkinElmer Life Science) and Alexa Fluor 555-conjugated streptavidin (Invitrogen). Nuclei were counterstained with DAPI (Invitrogen). Images
were acquired with LSM 750 confocal microscope and analyzed using ZEN software (both from Carl Zeiss MicroImaging Inc).

**Aldehyde dehydrogenase activity**

Aldehyde dehydrogenase activity of MACS-enriched MLN CD11c\(^+\) cells was determined using the ALDEFOUR staining kit (StemCell Technologies) according to the manufacturer's instructions and as described previously (Schulz et al., 2009).

**Microbiota analysis**

Cecal and colonic samples were collected after sacrifice and immediately frozen in liquid nitrogen. Microbial DNA was extracted using a NucleoSpin soil kit (Macherey-Nagel) according to manufacturer’s instructions. PCR-based library formation, sequencing (Illumina MiSeq), taxonomy assignment and subsequent data analysis were performed as previously described (Holm et al., 2015). The dataset contained an average of 33,296 and 28,404 sequences per sample before and after filtering, respectively. Assessment of significant differences was performed with the adonis test, using Bray Curtis distance, and metagenomeSeq (Paulson et al., 2013) for the effect on specific OTUs or phylotypes. All sequence data is available from the European Nucleotide Archive (ENA) with study accession number: PRJEB10856.

Quantitation of segmented filamentous bacteria (SFB) was performed using qPCR reactions run on 75ng of DNA using SFB-specific primers (SFB736F: 5\(^{-}\)-GAC GCT GAG GCA TGA GAG CAT-3\(^{'}\); SFB844R: 5\(^{-}\)-GAC GGC ACG GAT TGT TAT TCA-3\(^{'}\)) (Bouskra et al., 2008) and normalized to the total amount of bacterial DNA using total eubacteria-specific primers (27F 5\(^{-}\)’TCCTACGGGAGGCAGCAG T3\(^{'}\); 343R 5’ GACTACCAG GGTATCTAATCCTGT 3\(^{'}\)) (Marathe et al., 2012).
Trichuris muris infection

Mice received approximately 20 infective *T. muris* (strain E) eggs by oral gavage and worm burden and *T. muris*-specific serum IgG1 and IgG2a assessed 35 d post infection. To quantify worm burden, the cecum and proximal colon were removed, cut longitudinally, and worms collected and counted under a microscope. For analysis of *T. muris*-specific serum IgG1 and IgG2a levels, ELISA plates were coated overnight with *T. muris* antigen, prepared as previously described (Wakelin, 1967). After addition of serum for 2 h at room temperature, plates were washed and incubated with anti-mouse IgG1 (RMG1-1) and IgG2a biotin-conjugated antibodies (RMG2a-62; BioLegend) followed by streptavidin-conjugated horseradish peroxidase (BioLegend) and tetramethylbenzidine (BD Bioscience). The reaction was stopped by addition of H$_2$SO$_4$ (1M), and absorbance measured at 450 nm on a SPECTROstar Nano (BMG LABTECH).
**Primer Sequences, Related to Experimental Procedures**

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Supplemental references


Different populations of CD11b⁺ dendritic cells drive Th2 responses in the small intestine and colon

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T-helper 2 (Th2) cell responses defend against parasites. Although dendritic cells (DCs) are vital for the induction of T-cell responses, the DC subpopulations that induce Th2 cells in the intestine are unidentified. Here we show that intestinal Th2 responses against Trichuris muris worms and Schistosoma mansoni eggs do not develop in mice with IRF-4-deficient DCs (IRF-4f/fCD11c-cre). Adoptive transfer of conventional DCs, in particular CD11b-expressing DCs from the intestine, is sufficient to prime S. mansoni-specific Th2 responses. Surprisingly, transferred IRF-4-deficient DCs also effectively prime S. mansoni-specific Th2 responses. Egg antigens do not induce the expression of IRF-4-related genes. Instead, IRF-4f/fCD11c-cre mice have fewer CD11b⁺ migrating DCs and fewer DCs carrying parasite antigens to the lymph nodes. Furthermore, CD11b⁺CD103⁻ DCs induce Th2 responses in the small intestine, whereas CD11b⁺CD103⁺ DCs perform this role in the colon, revealing a specific functional heterogeneity among intestinal DCs in inducing Th2 responses.
Type 2 immunity, the typical response against parasitic or allergic stimuli, can protect against parasites or exacerbate allergic conditions. Approximately, one-third of the world’s population are infected with parasitic worms, most of which affect the gastrointestinal tract. Many of these infections develop into chronic pathologies and are an enormous global health burden. There is insufficient knowledge about how worm infections, which can selectively infect either the small intestine or the colon, are controlled by the intestinal immune system. Helminth parasite infections in both the small intestine and colon induce potent T-helper 2 (Th2) responses that can control parasite burden or lead to chronic pathologies. Schistosoma mansoni eggs and their soluble egg antigens (schistosome egg antigen, SEA) induce potent Th2 and interferon (IFN)-γ responses, both during infection with live parasites and in experimental models in which eggs or SEA are injected into tissues. During the natural parasite infection, a proportion of the eggs released by intravascular adult worms become lodged in the intestinal wall and the liver, where they induce strong type 2 immune responses. These eggs are central to immunopathology associated with this infection, as they induce granulomatous inflammation and tissue fibrosis, which can lead to severe organ damage.

In the small intestine and colon, four different populations of conventional DCs can be identified, categorized by their differential expression of the integrins CD11b and CD103 (refs 12–14). These populations are present at different frequencies in the small intestine and colon, and migrate via intestinal-draining lymphatics to the mesenteric lymph nodes (MLN) to initiate T-cell responses. Studies have indicated that intestinal DC populations are specialized to induce different facets of the T-cell response. For example, transcription factor IFN regulatory factor (IRF)-8-dependent intestinal CD11b+CD103+ (CD103 single-positive (SP)) DCs have a predominant function in cross-presentation to CD8+ T cells and induction of intestinal Th1 responses, whereas IRF-4-dependent CD11b+CD103+ (double-positive (DP)) DCs seem to drive Th17 cell differentiation in intestine-draining MLNs. Although the function of these populations in intestinal Th2 responses is unclear, studies have demonstrated that IRF-4 expression by CD11c+ cells is crucial for the development of Th2 responses. In the intestine, IRF-4 is predominantly expressed by CD11b+CD103+(CD103 SP) DCs and DP DCs, and IRF-4 deficiency in CD11c+ cells results in fewer small intestinal DP DCs, as well as the absence of DP DCs and fewer CD11b SP DCs in the draining MLNs.

To investigate how IRF-4-expressing DCs drive intestinal Th2 responses, we use two models of human parasite infection that drive Th2 responses in the gastrointestinal tract. We address the induction of Th2 responses in vivo by experimental immunization with S. mansoni eggs and validate our findings during live infection with the intestinal parasite Trichuris muris. We find that CD11b-expressing DCs are specialized to drive antigen-specific Th2 responses. Furthermore, different populations of CD11b+ IRF-4+ DCs induce Th2 responses in the small intestine and colon. DP DCs from the small intestine are the only population sufficient to induce antigen-specific Th2 responses in the small intestine-draining lymph nodes and CD11b SP DCs fulfill this function in colon-draining lymph nodes. We thus demonstrate that different DC populations have distinct functions in separate regions of the intestine, which is important for understanding how intestinal immune responses are controlled, and offers the opportunity to develop more precise therapeutic targets.

**Results**

**Intestinal Th2 responses require IRF-4-positive CD11c+ cells.** To identify the cellular mechanisms central to the induction of Th2 responses in the intestine we developed a novel method of experimental delivery of S. mansoni eggs directly into intestinal tissue. Eggs were injected directly into sites where they become trapped during live infection, thus providing a refined and relevant method to investigate the Th2 responses generated against trapped and penetrating eggs in the intestine (Supplementary Fig. 1a,b). The method also allowed precise temporal control of the induction of Th2 responses against S. mansoni eggs in the gastrointestinal tract in vivo, which has not been previously possible. We found that the injection of 1,000 S. mansoni eggs into the subserosal tissue of the small intestine was sufficient to induce antigen-specific Th2 and IFN-γ responses in the MLNs, with interleukin (IL)-4 and IL-13 induced in vivo total small MLN cultures, specifically after the restimulation with SEA 5 days after in vivo immunization (Fig. 1a and Supplementary Fig. 1c–e). Consistent with published findings, we observed no antigen-specific induction of Th17 cytokines (Supplementary Fig. 1d). Intracellular flow cytometric staining after phorbol 12-myristate 13-acetate (PMA)/ionomycin stimulation confirmed that these cytokines were produced by CD4 T cells that produced IFN-γ or had differentiated into Th2 cells (Fig. 1b and Supplementary Fig. 1f). To determine whether intestinal egg injection could also be used as a model of colonic Th2 induction, eggs were injected either in the small intestine or colon and the small intestine-draining MLNs (sMLNs) and colon-draining MLNs (cMLNs) were harvested 5 days after immunization. Analysis of restimulated individual lymph node revealed increased concentrations of antigen-specific cytokines, compared with analysis of pooled MLNs (Fig. 1a). These responses were only observed in the sMLNs or cMLNs draining the respective injection sites (Fig. 1c). Thus, intestinal S. mansoni egg injections can be used as an experimental model to further investigate the mechanisms of Th2 induction in both tissues.

Many aspects of type 2 immunity are controlled by the transcription factor IRF-4, which controls the development of Th2 cells, alternatively activated macrophages and CD11b+ macrophages. However, little is known about how IRF-4 regulates the induction of Th2 responses in the intestine. To determine what impact the expression of IRF-4 by antigen-presenting cells had in driving intestinal Th2 responses in the small intestine and colon, we used the IRF-4Cre+CD11c-cre mouse model that allows targeted deletion of IRF-4 cells for Th2 induction (Fig. 1d). The loss of IRF-4-dependent cells in these animals did not affect the total number of cells in the small intestine (Supplementary Fig. 2c). The impaired Th2 responses were evident in both the small intestine and colon, demonstrating a central requirement for IRF-4+CD11c+ cells for Th2 induction in both organs. When we assessed the expression of IRF-4 by DCs and macrophages we observed that a high percentage of DCs...
Figure 1 | Intestinal Th2 responses to S. mansoni eggs and T. muris worms are dependent on IRF-4⁺ CD11c⁺ cells. (a) One thousand S. mansoni eggs were injected into the subserosal layer of the small intestine and resulting T-cell responses were analysed after 5 days by restimulating MLN cells for an additional 3 days in the presence of SEA. Cytokines were measured from supernatants of restimulation cultures of unstimulated (Unstim) and restimulated (Restim) MLN cells (n = 9 mice, in three independent experiments, mean ± s.e.m., Mann–Whitney U-tests, ***P ≤ 0.001). (b) Five days after immunization with S. mansoni eggs (Egg inj), MLNs were harvested. CD44hi CD4 T cells identified by flow cytometry and levels of IFN-γ, IL-4 and IL-13 cytokine production measured after PMA/ionomycin stimulation and compared with cells harvested from naive animals (n = 10 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney U-tests, ***P ≤ 0.001). (c) Cytokine responses of individually harvested small intestinal (sMLN) and colonic (cMLN) draining lymph node restimulation cultures 5 days after small intestinal (left panel) or colonic (right panel) egg injection (n = 9 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney U-tests, *P ≤ 0.05, **P ≤ 0.01 and ***P ≤ 0.001). (d) Cytokine responses of restimulated MLN cells from small intestinal (left panel) or colonic (right panel) egg injected IRF-4f/fCD11c⁻ cre or littermate IRF-4f/fCD11c⁺ cre mice (n = 6 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney U-tests, ***P ≤ 0.001). (e) Cytokine responses of individually harvested small intestinal (sMLN) and colonic (cMLN) draining lymph node restimulation cultures 35 days after small intestinal (left panel) or colonic (right panel) egg injection (n = 9 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney U-tests, ***P ≤ 0.001). (f) Secreted cytokines after T. muris E/S antigen-specific restimulation of MLN cells 35 days after T. muris infection (n = 9 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney U-tests, ***P ≤ 0.001).

expressed IRF-4, whereas only a few macrophages were IRF-4⁺ (Supplementary Fig. 2d–g). Although macrophages expressed lower levels of IRF-4, a role for IRF-4 in these cells cannot be excluded. However, consistent with previous published work14,18,28, we found that macrophages were absent from thoracic duct lymph of mesenteric lymphadenectomized (MLNx) mice (Supplementary Fig. 3c) and are therefore unable to prime T-cell responses in the MLNs, excluding the possibility that IRF-4⁺ macrophages are necessary to prime Th2 responses.

To further address whether IRF-4 in DCs was necessary for Th2 induction, we performed DC transfer experiments.

To verify that IRF-4⁻ DCs were also necessary for establishing a physiological type 2 immune response against live parasites, cre⁺ and cre⁻ mice were infected with ~250–300 eggs from the nematode T. muris by oral gavage. Under these conditions, T. muris infection evokes a strong Th2 response in the colon of C57BL/6 mice that mediates expulsion within 35 days29. We observed that cre⁺ mice did not effectively clear adult worms by 35 days post infection, suggesting an inefficient type 2 immune response (Fig. 1e). Indeed Th2 responses were markedly decreased in cre⁺ mice and we observed reduced production of IL-9 and IL-13 in in vitro MLN restimulation cultures 35 days post infection (Fig. 1f).

Thus, Th2 responses to parasite antigen present in the small intestine or colon require IRF-4-expressing CD11c⁺ cells for their induction in the respective draining lymph nodes.

Lymph DCs prime responses to S. mansoni eggs. To determine which migratory cell populations were responsible for transporting parasite antigen from the periphery to the draining lymph nodes, AlexaFluor660 (AF660)-labelled SEA was injected into the intestinal serosa. To directly assess migrating cell populations, thoracic duct lymph was collected from MLNx mice for 18 h after SEA-AF660 injection, using previously described techniques14. We observed that among all lymph migrating cells, B cells and conventional DCs labelled positive for Alexa660-labelled SEA (Fig. 2a and Supplementary Fig. 3a). DCs were the most efficient population to transport SEA-AF660 from the intestine, representing the highest proportion of AF660-labelled cells. To determine which cells were capable of inducing SEA-specific immune responses in vivo, fluorescence-activated cell sorting (FACS)-purified donor cells from egg-injected animals were transferred under the MLN capsule of wild-type recipient mice. We have previously used this technique to assess DC functions in vivo30, inspired by an elegant study examining migration of transferred DCs into recipient lymph nodes30.

Intranodal DC transfer allowed the direct assessment of the in vivo priming capabilities of the transferred cells in their physiological location. Five days after cell transfer, the injected MLNs were harvested and restimulated with SEA in vitro to test for antigen-specific immune responses. DCs from egg-injected donors were the only cells able to induce antigen-specific immune responses upon cell transfer, whereas B cells—despite carrying antigen—could not drive antigen-specific immune responses after transfer (Fig. 2b). In agreement with previous experiments using BM-derived DCs in vivo31,28 or splenic DCs in vitro32, SEA-specific Th2 induction by intestinal lymph DCs required major histocompatibility complex II (MHCII) expression (Fig. 2c and Supplementary Fig. 3b), but was independent of their ability to produce IL-4 (Supplementary Fig. 3e).
Antigen-specific immune responses could also be induced by DCs incubated with SEA in vitro. FACS-purified DCs from the intestinal lamina propria (LP), the lymph, and the MLNs of wild-type C57BL/6 animals were cultured with SEA for 18 h and transferred into recipient animals. Transferred LP-derived and lymph DCs induced antigen-specific immune responses, measured in vitro restimulation cultures. However, SEA-loaded MLN DCs did not induce any antigen-specific responses after transfer (Fig. 2d).

Thus, conventional DCs are sufficient to drive S. mansoni egg antigen-specific immune responses in the intestinal draining lymph nodes, and process and present egg antigens to CD4 T cells in a MHCII-dependent manner.

Figure 2 | Conventional DCs drive immune responses against SEA in the MLN. (a) Transport of parasite antigen was assessed by injecting AF660-labelled SEA (SEA-AF660) into the small intestine of MLNx mice and measuring the percentage of fluorescent cells in intestinal draining lymph 18 h after injection. Representative FACS plots of SEA-transporting DCs from PBS (PBS inj) and SEA (SEA inj) injected mice (left panel), and percentage of SEA-transporting lymph migrating CD4 and CD8 T cells, B cells and DCs (DCs) (right panel) are shown (n = 7 mice in three independent experiments, mean ± s.e.m., Kruskal–Wallis test, ***P < 0.001). (b) Fifty thousand MHCII−/− CD64−/− B220−/− CD11c+ DCs and 100,000 B cells were purified from the lymph of egg-injected MLNx donor mice 18 h after injection and delivered under the MLN capsule of wild-type recipient mice. After 5 days, antigen-specific T-cell responses were measured in the injected MLNs by SEA restimulation for 3 days and subsequent cytokine measurement by ELISA (n = 7 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney U-tests, **P < 0.01). (c) Similar to (b). (d) Fifty thousand DCs were purified from the small intestinal LP (left panel), the lymph of MLNx mice (middle panel) or the MLNs (right panel) of C57BL/6 mice and loaded with SEA for 18 h in vitro. Unbound antigen was washed off and cells transferred under the MLN capsule of wild-type recipient animals. T-cell responses in the injected MLNs were measured 5 days after cell transfer by cytokine analysis of in vitro restimulation cultures with (Restim) or without (Unstim) SEA (n = 10 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney U-tests, **P < 0.01 and ***P < 0.001).

SEA treatment of DCs does not affect IRF-4–related genes. To identify the intestinal DC populations driving antigen-specific immune responses, lymph DCs were separated by their expression of CD11b and CD103 (Supplementary Fig. 3c). Thirty thousand cells of each population were separated from wild-type C57BL/6 MLNx lymph, incubated with SEA in vitro and transferred under the MLN capsule of wild-type recipient mice. Both, CD11b+/−CD103+ (CD11b single-positive (SP)) and CD11b−/−CD103+ double-positive (DP) DCs could induce antigen-specific Th2 and IFN-γ responses after transfer, whereas CD11b+/−CD103− double-negative (DN) and CD11b−/−CD103− (CD103 SP) DCs could only induce antigen-specific IFN-γ responses (Fig. 3a). Thus, only CD11b-expressing DC populations were specialized to induce Th2 responses, whereas all DC populations could induce antigen-specific IFN-γ. To understand the underlying molecular mechanisms that selectively enabled CD11b SP and DP DCs to prime antigen-specific Th2 responses, we performed microarray analysis and compared the gene expression profiles of sorted CD11b SP and DP DCs after in vitro incubation with or without SEA. Five thousand and eighteen significant loci of coding and non-coding gene elements were identified as differentially expressed between any of the four conditions (CD11b SP DCs/DP DCs, SEA-treated/untreated). Principal component analysis revealed clustering of replicate samples and a clear separation between the cell populations and between treatments (Fig. 3b). Several of the genes affected by SEA treatment have been shown to be involved in antigen presentation and T-cell differentiation, and 41 differentially expressed genes changed their expression levels more than 2-fold after SEA treatment of CD11b SP DCs. The highest fold changes were observed in downregulated MHCII-related genes, Ccl7 and Il1f9, which encode the proinflammatory cytokine IL-36γ. Costimulatory molecules such as Cd80 and Tnfaf1, which encodes Oxlol, and Rasgrp3 and Serpinb9b were upregulated by SEA treatment of CD11b SP DCs (Fig. 3c). Thirty-three genes were differentially expressed after SEA treatment of DP DCs and a downregulation of MHCII-related genes and Il1f9, and an upregulation of Rasgrp3 and Serpinb9b was again observed (Fig. 3c). We observed limited overlap between the differentially expressed genes with high fold
change (absolute fold change < −2; > 2) and analysis of variance P-value < 0.05) after SEA treatment of CD11b SP and DP DCs, which were Rasgrp3, H2-EB2 and Ili1f9 (Fig. 3d). However, none of these genes have previously been associated with Th2 cell polarization. Strikingly, IRF-4-associated genes did not change their expression profile upon treatment with SEA (Fig. 3e), despite the fact that IRF-4 expression by CD11c+ cells was required for the induction of Th2 responses against S. mansoni eggs and T. muris worms.

IRF-4 affects the migration of intestinal DCs. Our observation that egg antigens did not induce the expression of IRF-4-associated genes in DCs suggested that the defect of Th2 responses observed in IRF-4f/f CD11c-cre+ mice was not due to the defective induction of these genes. We therefore investigated whether other mechanisms were involved and assessed whether IRF-4 deletion in CD11c+ cells affected the number of each of the DC populations in the intestine. Consistent with reports in IRF-4f/f CD11c-cre+ mice, cre+ BM chimeras showed a
decrease in the DP DC population in the small intestine (Fig. 4a and Supplementary Fig. 4a). In the colon, a general decrease of DCs, again most strikingly observed in DP DCs, was observed (Fig. 4b). However, this developmental defect did not impair intestinal DC function. Antigen uptake, visualized by the injection of Alexa660-labelled SEA, was not affected in cre+ mice and comparable numbers of intestinal LP DCs labelled positive for SEA-AF660 18 h after injection in the small intestine and colon (Fig. 4c). Furthermore, transferred SEA-loaded DP DCs from the small intestinal LP of cre+ animals induced similar antigen-specific cytokine responses to C57BL/6 specific intestinal LP DCs after transfer into wild-type recipient animals (Fig. 4d). Thus, IRF-4 deficiency in CD11c+ cells influenced the development of intestinal LP DCs, in particular the DP DC population, and the numbers of CD11b-expressing DCs in the MLN, but did not inhibit the ability of the remaining intestinal DCs to drive Th2 cell differentiation.

To investigate whether the IRF-4-dependent reduction of LP DCs was reflected in the draining lymph nodes, we analysed DC populations in the MLNs from the transferred cre+ and the control mouse MLNs. We observed a 50% reduction of migratory CD11b SP DCs and a near absence of migratory DP DCs in the sMLNs, as previously observed. Reciprocally, the percentage of migratory CD103 SP DCs increased dramatically, but total numbers of CD103 SP DCs were not affected by the deletion of IRF-4 (Fig. 4e and Supplementary Fig. 4b). Migratory DC populations were affected to a similar extent in the cMLNs, where numbers of CD11b SP were reduced by half, DP DCs became almost absent and the numbers of CD103 SP DCs remained unaffected by the deletion of IRF-4 (Fig. 4f). Similar to LP DCs, the T-cell priming capabilities of these migratory MLN DC populations were not affected by the deletion of IRF-4. In vitro co-cultures ovalbumin (OVA), pulsed migratory DC populations from the sMLNs and cMLNs of cre+ animals drove equivalent proliferation of OVA-specific OT-II CD4+ T cells compared with their cre− counterparts (Fig. 4g and Supplementary Fig. 4c). In contrast, antigen delivery to the MLNs was strongly affected in vivo. Eighteen hours after AF660-SEA injection into the small intestinal or colonic LP, the number of AF660-SEA + DCs was greatly reduced in the sMLNs and cMLNs of cre+ animals (Fig. 4h). Thus, IRF-4 deficiency in CD11c+ cells did not influence the capacity of DCs to prime T cells and drive Th2 differentiation, consistent with our conclusions from gene expression analysis. Rather, the striking loss of migratory CD11b SP and DP DCs from the draining lymph nodes, combined with the decrease in the amount of transported parasite antigen, were the probable cause of the inadequate intestinal Th2 responses observed in IRF-4−/− CD11c+cre+ animals.

**Distinct DCs drive Th2 response in small intestine and colon.** As the composition of CD11b-expressing DC populations varies between the small intestine and colon, we assessed whether tissue-specific roles could be attributed to CD11b SP and DP DCs in priming intestinal Th2 responses. To directly assess the migration of DCs from the small intestine to the sMLNs, where priming occurs, we collected DCs from thoracic duct lymph from small intestinal sMLN (sMLNs) mice. We observed that DP DCs, the most abundant DC population in the small intestine, migrated at an increased frequency, compared with PBS-injected controls, after the injection of *S. mansoni* eggs into the small intestine (Fig. 5a and Supplementary Fig. 5a,c). DP DCs were also the predominant population to transport small intestinaly injected SEA-AF660 in sMLN lymph (Fig. 5b). Importantly, the transfer of FACS-purified sMLN lymph DC populations from egg-injected donor mice into recipient animals revealed that CP DCs were the only population sufficient to drive antigen-specific immune responses after transfer (Fig. 5c). This was confirmed after SEA loading of small intestinal LP DC populations, to ensure that any differences in antigen availability did not influence the results. Again, DP DCs were the most efficient population to prime antigen-specific Th2 responses against egg antigens. Similar to our previous observations, IFN-γ responses could be induced by all DC populations (Fig. 5d).

Thus, DP DCs specialize in transporting and presenting *S. mansoni* egg antigens from the small intestine and prime antigen-specific Th2 cells in the draining lymph nodes.

**Examination of DC populations migrating from the colon revealed a different picture.** In contrast to the small intestine, CD11b SP DCs migrated in increased frequency in colon-draining sMLN lymph after the injection of *S. mansoni* eggs into the colon (Fig. 5e and Supplementary Fig. 5b,d). As well as being the predominant DC population within the colonic LP, CD11b SP DCs were the only population to carry fluorescently labelled SEA-AF660 in the lymph after colonic injection (Fig. 5f). Furthermore, colonic CD11b SP LP DCs were the most efficient at inducing Th2 responses against *in vitro*-loaded SEA after transfer (Fig. 5g).

Thus, in contrast to the small intestine, CD11b SP DCs were responsible for transporting and presenting *S. mansoni* egg antigens from the colon and were the most efficient population for priming antigen-specific Th2 cells in the colon-draining lymph nodes.
Figure 4 | IRF-4 deficiency alters DC population composition to reduce antigen availability in the MLNs. (a) Representative percentages and total numbers of CD11b and CD103-expressing DC populations from the small intestines of IRF-4-deficient (Cre−) or littermate IRF-4-deficient (Cre+) bone-marrow (BM) chimeras (n=8 mice per group, in three independent experiments, mean ± s.e.m., Mann-Whitney U-tests, *P<0.05 and **P<0.01). (b) Representative percentages and total numbers of DC populations from the colon of cre− and cre+ BM chimeras (n=8 mice per group, in three independent experiments, mean ± s.e.m., Mann-Whitney U-tests (not significant)). (c) Thirty-thousand CD11b+ CD103+ double-positive (DP) DCs from the small intestine of C57BL/6 or cre− BM chimeras were incubated with SEA for 18 h in vitro and transferred under the MLN capsule of wild-type recipient animals. Antigen specific T-cell responses in the injected MLNs were measured 5 days after cell transfer by cytokine analysis of in vitro SEA restimulation cultures (n=6 mice per group, in three independent experiments, mean ± s.e.m., Mann-Whitney U-tests (IFN-γ) = 0.59, (IL-4) = 0.82, (IL-5) = 0.09 and (IL-13) = 0.50). (d) Representative percentages and total numbers of DC populations from the sMLNs of cre− and cre+ BM chimeras (n=5-12 mice per group, in three independent experiments, mean ± s.e.m., Mann-Whitney U-tests, ***P<0.001). (e) Representative percentages and total numbers of DC populations from the colonic draining MLNs (sMLNs) of cre− and cre+ BM chimeras (n=12 mice per group, in three independent experiments, mean ± s.e.m., Mann-Whitney U-tests, **P<0.01). (f) Six thousand sMLN (left panel) or 3,000 eMLN (right panel) DC populations from cre− and cre+ BM chimeras were pulsed with OVA and co-cultured with CFSE-labelled OT-II MLN cells for 3 days. In vitro OT-II CD4 T-cell proliferation was assessed by CFSE dilution and compared between cre+ and cre− DC populations (n=3-16 duplicate cocultures per group, in three independent experiments, mean ± s.e.m., Mann-Whitney U-tests (not significant)). (g) Transport of SEA-AF660 by cre+ and cre− migratory DCs to the draining lymph nodes 18 h after injection into the small intestine or colon. Representative FACS plots from the sMLN (left panel) and total numbers of SEA-AF660+ migratory sMLN (middle panel) and cMLN (right panel) DCs are shown (n=8 mice per group, in three independent experiments, mean ± s.e.m., Mann-Whitney U-tests, *P<0.05 and ***P<0.001).
Figure 5 | Th2 responses in the small intestine and colon are driven by distinct CD11b+ DCs. (a) Frequency of lymph migrating DC populations 18 h after the injection of PBS (PBS inj) or S. mansoni eggs (Egg inj) into the small intestine of sMLNx C57BL/6 animals (n = 10–11 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney U tests (CD11b SP) = 0.25, (PDP) = 0.02, (CD103 SP) = 0.04 and (PDN) = 0.14). (b) Transport of AF660-labelled SEA (SEA-AF660) by lymph-migrating DC populations 18 h after small intestinal injection into sMLNx animals. Representative FACS plots from CD11b+ SP and DP DCs (left panel) and total numbers of CD11b+ DC populations 18 h after the injection of PBS (PBS inj) or SEA-AF660 (SEA inj) into the colon of C57BL/6 mice (n = 6 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney tests). **(P = 0.01). (c) Transport of SEA-AF660 by lymph-migrating DC populations 18 h after small intestinal injection into sMLNx animals. Representative FACS plots from CD11b+ SP and DP DCs (left panel) and total numbers of CD11b+ DC populations (right panel) are shown (n = 5 mice per group in two independent experiments, mean ± s.e.m., Kruskal–Wallis test, ***P ≤ 0.001). (d) Thirty-thousand DCs from each population were isolated from the lymph of small intestinal egg-injected sMLNx mice and transferred under the MLN capsule of wild-type recipient animals. Antigen-specific immune responses were analysed as in (c) (n = 6 mice per group, in three independent experiments, mean ± s.e.m., Kruskal–Wallis test, ***P ≤ 0.001). (e) Frequency of lymph-migrating DC populations 18 h after the injection of PBS or S. mansoni eggs into the colon of colonic MLNx (cMLNx) C57BL/6 animals (n = 6–7 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney U-tests (P) = 0.17, (P) = 0.17, (P) = 0.22 and (P) = 0.71). (f) Transport of SEA-AF660 by lymph-migrating DC populations 18 h after injection into the colon of cMLNx animals. Representative FACS plots from CD11b SP and DP DCs (left panel), and total numbers of CD11b+ DC populations (right panel) are shown (n = 5 mice per group, in two independent experiments, mean ± s.e.m., Kruskal–Wallis test, **P ≤ 0.01). (g) Thirty-thousand DCs from each population were isolated from the colon of C57BL/6 mice, incubated with SEA in vitro and transferred under the MLN capsule of wild-type recipient animals. Antigen-specific Th2 responses in the small intestine and colon are driven by distinct CD11b+ DCs. (a) Frequency of lymph migrating DC populations 18 h after the injection of PBS (PBS inj) or S. mansoni eggs (Egg inj) into the small intestine of sMLNx C57BL/6 animals (n = 10–11 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney U tests (CD11b SP) = 0.25, (PDP) = 0.02, (CD103 SP) = 0.04 and (PDN) = 0.14). (b) Transport of AF660-labelled SEA (SEA-AF660) by lymph-migrating DC populations 18 h after small intestinal injection into sMLNx animals. Representative FACS plots from CD11b+ SP and DP DCs (left panel) and total numbers of CD11b+ DC populations 18 h after the injection of PBS (PBS inj) or SEA-AF660 (SEA inj) into the colon of C57BL/6 mice (n = 6 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney tests). **(P = 0.01). (c) Transport of SEA-AF660 by lymph-migrating DC populations 18 h after small intestinal injection into sMLNx animals. Representative FACS plots from CD11b+ SP and DP DCs (left panel) and total numbers of CD11b+ DC populations (right panel) are shown (n = 5 mice per group in two independent experiments, mean ± s.e.m., Kruskal–Wallis test, ***P ≤ 0.001). (d) Thirty-thousand DCs from each population were isolated from the lymph of small intestinal egg-injected sMLNx mice and transferred under the MLN capsule of wild-type recipient animals. Antigen-specific immune responses were analysed as in (c) (n = 6 mice per group, in three independent experiments, mean ± s.e.m., Kruskal–Wallis test, ***P ≤ 0.001). (e) Frequency of lymph-migrating DC populations 18 h after the injection of PBS or S. mansoni eggs into the colon of colonic MLNx (cMLNx) C57BL/6 animals (n = 6–7 mice per group, in three independent experiments, mean ± s.e.m., Mann–Whitney U-tests (P) = 0.17, (P) = 0.17, (P) = 0.22 and (P) = 0.71). (f) Transport of SEA-AF660 by lymph-migrating DC populations 18 h after injection into the colon of cMLNx animals. Representative FACS plots from CD11b SP and DP DCs (left panel), and total numbers of CD11b+ DC populations (right panel) are shown (n = 5 mice per group, in two independent experiments, mean ± s.e.m., Kruskal–Wallis test, **P ≤ 0.01). (g) Thirty-thousand DCs from each population were isolated from the colon of C57BL/6 mice, incubated with SEA in vitro and transferred under the MLN capsule of wild-type recipient animals. Antigen-specific Th2 responses in the small intestine and colon are driven by distinct CD11b+ DCs.
Discussion

Many cell types have been implicated in inducing type 2 immune responses against S. mansoni egg antigens, including monocyte-derived DCs, conventional DCs31 and basophils33. In this context, the intestine is an important tissue, being heavily affected by penetrating S. mansoni eggs during live infection, and the target of many Th2-inducing helminth parasite infections35. To investigate which cell populations are sufficient to induce intestinal Th2 responses, we established an experimental immunization procedure for controlled delivery of eggs into intestinal subserosal tissue. We observe that egg antigen-specific CD4 T-cell responses are induced in the draining MLNs (Fig. 1), which, as previously reported34,35,36, produced both IFN-γ and the Th2-associated cytokines IL-4, IL-5 and IL-13. S. mansoni eggs induce antigen-specific immune responses in both the small intestinal and colonic draining lymph nodes after injection into the respective tissues. IRF-4-expressing CD11c+ cells are critical for the induction of Th2 responses both in the small intestine and colon (Fig. 1), as Th2 immune responses did not develop in IRF-4−/−CD11c−/+ mice, suggesting previous reports in the lung35 and the small intestine during Nippostrongylus brasilensis infection20.

As CD11c is expressed by monocyte-derived DCs, conventional DCs and macrophages in the intestine37, we address which specific cell population transports egg antigen from the intestine to the draining lymph nodes and is sufficient to drive antigen-specific immune responses. Injection of fluorescently labelled SEA enables identification of B cells and conventional DCs transporting egg antigens to the MLN. Transfer of cells directly under the MLN capsule allows for delivery of cells by their physiological route of entry and to assess their priming capabilities in vivo15,30. MHCI-expressing DCs, but not B cells, from egg-injected donor mice are sufficient to induce egg antigen-specific immune responses in the recipient MLN (Fig. 2). Furthermore, both intestinal LP DCs and lymph DCs isolated from wild-type C57BL/6 mice can present SEA after in vitro incubation. Thus, our data indicate that conventional DCs transport parasite antigen from the intestine to the draining lymph nodes and are sufficient to directly prime antigen-specific immune responses. Further analysis of the four intestinal DC populations that can be defined by the expression of CD11b and CD103 (refs 12–14) reveals that SEA-loaded CD11b+CD103− single-positive (CD11b SP) and CD11b+CD103+ double-positive (DP) DCs are specialized to prime antigen-specific Th2 and IFN-γ responses upon transfer, whereas CD11b+CD103− double-negative (DN) and CD11b−CD103+ single-positive (CD103 SP) DCs can only induce IFN-γ responses (Fig. 3). This observation is in line with previous findings that demonstrate that CD11b-expressing DCs from the spleen, lung and skin induce Th2 responses34,35,36–40. In contrast, CD103 SP DCs have been shown to negatively regulate Th2 responses, by their constitutive expression of IL-12 (ref. 41). The balance between the different DC populations is therefore critical for determining the outcome of the T-cell response.

Microarray analysis of the Th2-priming CD11b-expressing DCs reveals that the expression levels of genes involved in antigen presentation and T-cell differentiation are influenced by incubating CD11b SP and DP DCs with SEA. For example, Ccl8 and Tnfifs6, which encodes OX40L, are upregulated by SEA. These costimulatory markers are required for T-cell differentiation and OX40L has been previously been shown to be induced by SEA42. Furthermore, the downregulation of MHCI-related genes, proinflammatory mediators such as IL-36γ, encoded by Il1f9, and proinflammatory cytokine Ccl17, which has been shown to recruit proinflammatory Th2 cells during allergy43 could suggest that SEA dampens proinflammatory responses, as previously observed in vitro and in vivo8,32,44.

We anticipated that our expression analysis would reveal genes induced in both CD11b-expressing DC populations that contribute to their common ability to prime Th2 responses. However, we observe little overlap and only three genes are differentially expressed in SEA-cultured CD11b SP and DP DCs. Rasgrp3 is upregulated, whereas H2-Elb2 and Il1f9 are downregulated upon SEA incubation in both populations. RAS activators, such as RasGRP3, provide a key link between cell surface receptors and RAS activation, and RasGRP3 has been shown to control CCR9-dependent entry of early thymic progenitors in the thymus45, B-cell receptor signalling46 and the production of Toll-like receptor (TLR)-triggered proinflammatory cytokines in macrophages47. Together with the downregulation of H2-Elb2 and Il1f9, a dampening of proinflammatory responses is thus observed in these SEA-cultured DCs. However, no direct involvement of these genes in type 2 immune response has previously been reported and comparison with data sets from Th2-impaired Mbd2−/− bone-marrow DCs39 reveal no commonality. Surprisingly, the expression of IRF-4 and its binding partner Mgl2 (refs 20,49), Pdcd1lg2 (refs 50,51), which encodes PD12, Stat648 and Mbd2 (ref. 35) are also not upregulated by SEA (Fig. 3), leading us to conclude that S. mansoni egg antigens induce the ability to drive Th2 polarization in intestinal DCs by mechanisms that may not be revealed by gene expression analysis.

A key element of our work is that we have discovered that IRF-4 deficiency does not directly interfere with intestinal DC ability to induce T-cell priming or drive Th2 differentiation (Fig. 4), despite being previously suggested in the literature21,15. Rather, IRF-4 deficiency limits the number of intestine-derived CD11b-expressing DCs in the draining lymph nodes, consistent with previous observations in the intestine13 and the skin12. Impaired survival12,13 and lack of migration54 have both been suggested to cause this pronounced IRF-4–dependent decrease in CD11b-expressing DCs. As a result, limited amounts of egg antigen are present in the MLNs of IRF-4−/−CD11c−/+ mice, which probably causes the impaired Th2 responses in these mice (Fig. 4). Thus, IRF-4 does not directly control the ability of intestinal DCs to polarize Th2 cells, but rather affects the number of CD11b-expressing DCs, probably by influencing their differentiation and survival, and thus the amount of presented antigen in the draining lymph nodes.

As the composition of CD11b-expressing DCs varies along the gastrointestinal tract, we assessed whether CD11b SP and DP DC populations play tissue-specific roles. We and others have observed that DP DCs are the most abundant DCs in the small intestine, whereas CD11b SP DCs are more frequent in the colon15,18. These differences can be observed within the lamina propria (LP), as well as in tissue-specific draining lymph, and the respective draining lymph nodes55. We observe that small intestinal egg antigen-driven DCs are present at increased frequency within lymph, suggesting increased migration (Fig. 5). It is well established that TLR activation can lead to DC migration in the intestine, which has been shown for R848 (ref. 55), a TLR7/8 agonist, and soluble flagellin3,56, which activates TLR5. DCs do not require MyD88-mediated TLR signalling to induce Th2 responses57, but the effects of S. mansoni eggs on DC migration have not previously been addressed. Diverse pathogen-associated molecular patterns, such as Omega-1, have been identified in S. mansoni eggs and SEA36,59,
indicating that a range of parasite molecules may influence DC migration.

As well as displaying increased migration, DP DCs are the most numerous population to carry fluorescently labelled SEA from the small intestine to the draining lymph nodes. Transfer of purified DC populations from egg-injected donor mice reveals that DP DCs are also the only DCs capable of inducing antigen-specific immune responses in recipient animals (Fig. 5). This is likely to be both due to their ability to capture egg antigen but also an intrinsic specialisation for inducing Th2 responses, which we verified by transfer of in vitro SEA-loaded small intestinal LP DCs. In this system, all populations can induce antigen-specific IFN-\(\gamma\) responses but only DP DCs induce strong Th2 responses, suggesting that DP DCs from the small intestine are either specialized to process and present specific Th2-inducing antigens within SEA or, more probably, can generate specific signals that drive the differentiation of Th2 cells. In contrast to the small intestine, CD11b SP DCs migrate in increased frequency in lymph of egg-injected animals after colonic egg injection, transport fluorescently labelled SEA from the colon and are the predominant population to induce Th2 responses when loaded with SEA (Fig. 5). Unexpectedly therefore, the Th2-inducing DC populations in the small intestine and colon are different, revealing unappreciated complexity in the functional specialisation of DCs in different tissues.

We thus demonstrate that specific populations of intestinal CD11b-expressing DCs are specialized to prime Th2 cells in the small intestine and colon, and speculate that this capacity extends beyond antigens from S. mansoni eggs and may also be relevant for other parasitic antigens or intestinal food allergens. The differences in the functions of CD11b-expressing DC populations between the small intestine and colon also provide clear evidence that the induction of immune responses in these tissues is controlled differently. This idea is supported by recent findings that have demonstrated that oral tolerance in the small intestine and colon are controlled differently. This idea is supported by recent findings that have demonstrated that oral tolerance in the small intestine and colon are controlled differently. This idea is supported by recent findings that have demonstrated that oral tolerance in the small intestine and colon are controlled differently. This idea is supported by recent findings that have demonstrated that oral tolerance in the small intestine and colon are controlled differently. This idea is supported by recent findings that have demonstrated that oral tolerance in
Set and intracellular staining was performed following the manufacturer’s instructions. Cells were analysed using a LSRII flow cytometer running FACSDiva Software (BD Bioscience) and analysed using FlowJo Software (Tree Star). 7AAD was used to discriminate live from dead cells from analysis. For cell sorting, DCs were gated on by selecting live CD45+ CD45RB200− CD64− Ly6C− CD11c+ MHCII+ single cells and individual CD11b+CD103+ expressing populations were sorted using an AriaII cell sorter (BD Bioscience). Cells undergoing subsequent antigen loading were incubated in supplemented (as above) X-vivo 15 media (Lonza) with 15 µg ml−1 SEA for 18 h or 2 mg ml−1 OVA protein (Sigma-Alrich) for 2 h at 37°C and 5% CO2.

**In vitro cell stimulation.** For intracellular staining experiments 2 × 10^6 MLN cells were incubated in RPMI 1640 supplemented with 2.5 ng ml−1 PMA (Sigma-Alrich), 1 µg ml−1 ionomycin (Invitrogen), 0.5% Golgistop (BD Bioscience) and 10% FCS for 4 h at 37°C, after which cell surface markers were stained. Cells were then fixed and permeabilized using the eBioscience Foxp3/Transcription Factor Staining Pico Assay 1.0. RNA samples were applied to a Mouse Transcriptome Array 1.0. Microarray analysis at Hologic Ltd using the Affymetrix Mouse Transcriptome (as above) was isolated with the RNeasy micro kit (Qiagen) and prepared for microarray analysis at Hologic Ltd using the Affymetrix Mouse Transcriptome Pico Assay 1.0. RNA samples were applied to a Mouse Transcriptome Array 1.0 (Affymetrix). Scanned CEL files were background corrected, normalized and summarized using the Affymetrix Expression Console Software 1.4. Differential gene expression was analysed using the Affymetrix Transcription Analysis Console Software 3.0 and visualized using Prism 6 Software (GraphPad). Principal component analysis analysis and heatmap visualization were conducted using ClustVis62.

**Microarray analysis.** Total RNA from SEA-activated lymph DC populations (as above) was isolated with the RNeasy micro kit (QIAGEN) and prepared for microarray analysis at Hologic Ltd using the Affymetrix Mouse Transcriptome Pico Assay 1.0. RNA samples were applied to a Mouse Transcriptome Array 1.0 (Affymetrix). Scanned CEL files were background corrected, normalized and summarized using the Affymetrix Expression Console Software 1.4. Differential gene expression was analysed using the Affymetrix Transcription Analysis Console Software 3.0 and visualized using Prism 6 Software (GraphPad). Principal component analysis analysis and heatmap visualization were conducted using ClustVis62.

**Statistical analysis.** Based on analyses of preliminary experiments, group sizes were chosen to ensure that a twofold difference between means, where the common standard deviation was less than or equal to half of the smaller mean, could be detected with a power of at least 80%. Primer 6 Software (GraphPad) was used to calculate the s.e.m. and statistical differences between groups were calculated using Mann–Whitney U-tests and Kruskal–Wallis tests, where appropriate, with P<0.05 being considered as significant.

**Data availability.** Microarray gene expression data are available from the Gene Expression Omnibus, accession number GSE91381. All other relevant data are available from the authors.

**References**


Acknowledgements

We thank V. Corovic, S. Houston, A. Schridde, A. Ivens and L. Webb for their guidance and advice, and the staff of the Central Research Facility and the Institute of Infection, Immunology and Inflammation Flow Cytometry Facility at the University of Glasgow for their assistance. We also thank S. Brown for technical support in generation of S. mansoni eggs and SEA, using infected snails that were supplied by the National Institute of Allergy and Infectious Diseases Schistosomiasis Resource Center at the Biomedical Research Institute (Rockville, MD), through contract HHSN272201000051D distributed through BEI Resources, with the help of M. Wilson (The Francis Crick Institute). This work was supported by grants from the Wellcome Trust to J.U.M. and S.W.M. (099784/Z/12/Z), and by a grant from the Medical Research Council (MR/R021099/1) to S.W.M. A.S.M. is part of the MCCR, which is a joint venture between the University of Manchester, GSK and AstraZeneca. This work was also supported by a Supere Aude III senior research grant from the Danish research council, the Lundbeckfonden (grant number R135-2014-4184) and grants from the Swedish research council to W.W.A. and grants from the Swedish Research Council, and the Crafoord, Carl Trygger and Per Eric & Ulla Schyberg Foundations to M.S.-F.

Author contributions

J.U.M. and M.D. performed the experiments. W.W.A., A.S.M. and M.S.-F. provided reagents and with S.W.M. helped direct the study. J.U.M. conceived the project with J.U.M. and S.W.M. (099784/Z/12/Z), and by a grant from the Medical Research Council (MR/R021099/1) to S.W.M. A.S.M. is part of the MCCR, which is a joint venture between the University of Manchester, GSK and AstraZeneca. This work was also supported by a Supere Aude III senior research grant from the Danish research council, the Lundbeckfonden (grant number R135-2014-4184) and grants from the Swedish research council to W.W.A. and grants from the Swedish Research Council, and the Crafoord, Carl Tryger and Per Eric & Ulla Schyberg Foundations to M.S.-F.

Additional information

Supplementary Information accompanies this paper at http://www.nature.com/naturecommunications

Competing interests: The authors declare no competing financial interests.

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Supplemental information

Different populations of CD11b+ dendritic cells drive Th2 responses in the small intestine and colon

Supplementary Figure 1. Intestinal Th2 responses to *Schistosoma mansoni* eggs induce antigen specific IFN-γ and Th2 responses. (a) Schematic illustrating the injection of *S. mansoni* eggs into the intestine. (b) Photographs taken during the injection procedure into the murine small intestine. Insertion of the syringe into the subserosal layer (left panel), injection of the eggs (middle panel) and deposited eggs after the removal of the syringe (right panel) are shown. Scale bar corresponds to 1 mm. (c) Schematic illustrating the experimental set up for immunization. 1,000 *S. mansoni* eggs were injected into the subserosal layer of the intestine and resulting T cell responses were analyzed after 5 days by restimulating mesenteric lymph node (MLN) cells for an additional 3 days in the presence of schistosome egg antigen (SEA) and measuring the released cytokines by ELISA. (d) Cytokine responses of restimulated MLN cells from PBS injected (PBS inj) and egg injected (egg inj) mice (n=9 mice per group, in three independent experiments, mean ± SEM, Mann-Whitney *U* tests, ***P≤0.001). (e) Cytokine responses of restimulated MLN cells from egg injected mice, where 500, 1,000 or 2,500 eggs were injected (n=4-6 mice per group, in two
independent experiments, mean ± SEM, Kruskal Wallis tests (not significant)).

(f) Corresponds to data shown in Fig. 1b. Representative gating strategy of
MLN cells harvested from egg injected animals five days after immunization.
CD44^{hi} CD4 T cells were identified by flow cytometry and levels of IFN-γ, IL-4
and IL-13 cytokine production measured after PMA/ionomycin stimulation and
compared to cells harvested from naive animals. (g) Five days after
immunization with *S. mansoni* eggs (egg inj), MLNs were harvested, CD44^{hi}
CD4 T cells identified as in (f) and levels of the Th2 associated transcription
factor GATA-3 measured by flow cytometry and compared to cells harvested
from naive animals (n=6 mice per group, in two independent experiments,
mean ± SEM, Mann-Whitney *U* tests, **P≤0.01).
Supplementary Figure 2. Intestinal DCs and macrophages are completely reconstituted in IRF4<sup>ff</sup> CD11c-cre positive and cre-negative bone marrow chimeric mice. (a) Representative gating strategy identifying small intestinal macrophages and dendritic cells (DC) from IRF4<sup>ff</sup> cre-negative (cre-) bone marrow (BM) chimeric mice. (b) The percentage of reconstitution was measured in IRF4<sup>ff</sup> CD11c-cre positive (cre+) or littermate cre- BM chimeric mice. Live cells, intestinal macrophages and DCs, as gated in (a), were analyzed (n=5 mice per group, in two independent experiments, mean ± SEM, Mann-Whitney U tests (not significant)). (c) Total cell numbers of enzymatically digested small intestines, colons and their respective draining lymph nodes were compared between cre+ or littermate cre- BM chimeras (n=8-20 mice per group, in more than three independent experiments, mean ± SEM, Mann-Whitney U tests (not significant)). (d) Corresponds to data shown in Fig. 2d. Representative gating strategy identifying small intestinal macrophages and DCs from C57BL/6 mice. (e) IRF4 expression by intestinal macrophages and DCs, as gated in (d), analyzed by flow cytometry in
C57BL/6 mice, and gated on the appropriate isotype control. (f) Representative gating strategy of enzymatically digested small intestinal mesenteric lymph node (sMLN) cells of cre- animals to identify migratory DCs and their CD11b and CD103 expressing populations. (g) Representative IRF4 expression of sMLN and colonic MLN (cMLN) CD11b+CD103− single positive (CD11b SP) and CD11b+CD103+ double positive (DP) DCs from cre+ and cre- animals, as gated in (f). (h) Representative FACS plots depicting Ly6C^{hi} monocytes and mature Ly6C^{lo} MHCII+ macrophages in C57BL/6 mice and cre+ and cre- BM chimeras.
Supplementary Figure 3. Lymph migrating DCs can be identified in intestinal draining lymph and can induce Th2 responses independent of their expression of IL-4. (a) Corresponds to data shown in Fig. 2a,b. Representative gating strategy of lymph migrating CD4 and CD8 T cells, B cells and dendritic cells (DCs) in intestinal draining lymph collected from mesenteric lymphadenectomized (MLNx) C57BL/6 animals for 18 hours. (b) Corresponds to data shown in Fig. 2c. Representative gating strategy of lymph migrating CD11c<sup>hi</sup> CD64<sup>-</sup> B220<sup>-</sup> DCs from MHCII<sup>-/-</sup> MLNx mice. (c) Corresponds to data shown in Fig. 2d and 3a. Representative gating strategy of lymph migrating MHCII<sup>hi</sup> CD64<sup>-</sup> B220<sup>-</sup> CD11c<sup>hi</sup> DCs from MLNx mice, identifying the four CD11b and CD103 expressing DC populations. (d) Representative sort purity of lymph migrating MHCII<sup>hi</sup> B220<sup>-</sup> CD11c<sup>hi</sup> DCs from MLNx mice. (e) 30,000 DP DCs from the lymph of C57BL/6 or IL-4<sup>-/-</sup> MLNx mice were incubated with schistosome egg antigen (SEA) for 18 hours in vitro and transferred under the mesenteric lymph node (MLN) capsule of wild type recipient animals. Antigen specific T cell responses in the injected MLNs were measured 5 days after cell transfer by cytokine analysis of in vitro SEA restimulation cultures (n=6 mice per group, in three independent experiments, mean ± SEM, Mann-Whitney U tests (not significant)).
Supplementary Figure 4. CD11b and CD103 expressing DC populations can be identified in the intestine and lymph nodes of IRF4<sup>fl/fl</sup> CD11c-cre positive and cre-negative bone marrow chimeric mice. (a) Corresponds to data shown in Fig. 4a-d. Representative gating strategy for enzymatically digested small intestinal lamina propria cells of IRF4<sup>fl/fl</sup> cre-negative (cre-) bone marrow (BM) chimeric mice to identify CD11b and CD103 expressing dendritic cell (DC) populations. Equivalent analysis was performed in IRF4<sup>fl/fl</sup> CD11c-cre positive (cre+) animals and the colon. (b) Corresponds to data shown in Fig. 4e,f,h. Representative gating strategy of enzymatically digested small intestinal mesenteric lymph node (sMLN) cells of cre- chimeric mice to identify migratory DC populations. Equivalent analysis was performed in cre+ animals and in the colon draining colonic MLNs. (c) Corresponds to data shown in Fig. 4g. Representative gating strategy identifying proliferated OT-II CD4 T cells, by their diluted concentration of CFSE, after 3 days of coculture with OVA-pulsed cre+ or cre- MLN DC populations.
Supplementary Figure 5. CD11b and CD103 expressing dendritic cell populations can be identified in small intestinal and colonic draining lymph. (a) Corresponds to data shown in Fig. 5a-c. Representative gating strategy of lymph migrating dendritic cell (DC) populations from small intestinal mesenteric lymphadenectomized (sMLNx) C57BL/6 animals that specifically drain from the small intestine. (b) Corresponds to data shown in Fig. 5e,f. Representative gating strategy of colon draining lymph migrating DC populations from colonic mesenteric lymphadenectomized (cMLNx) mice. (c) Total number of lymph migrating DC populations, as gated in (a), 18 hours after the injection of PBS (PBS inj) or Schistosoma mansoni eggs (egg inj) into the small intestine of sMLNx animals (n=10-11 mice per group, in three independent experiments, mean ± SEM, Mann-Whitney U tests (not significant)). (d) Total number of lymph migrating DC populations, as gated in (b), 18 hours after the injection of PBS or S. mansoni eggs into the colon of cMLNx animals (n=6-7 mice per group, in three independent experiments, mean ± SEM, Mann-Whitney U tests (not significant)).
Distinct DC subsets regulate adaptive Th1 and 2 responses during *Trichuris muris* infection

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Funding information
Carl Tryggers Stiftelse för Vetenskaplig Forskning; Crafoordska Stiftelsen; Vetenskapsrådet; Stiftelsen Sigurd and Elsa Goljes Minne; Per-Eric and Ulla Schyberg’s Foundation

Summary
Low- and high-dose infections with the murine large intestinal nematode *Trichuris muris* are associated with induction of adaptive Th1 and Th2 responses, respectively, in mesenteric lymph nodes (MLN). Classical dendritic cells (cDC) accumulate in the large intestinal mucosa and MLN upon *T. muris* infection, yet their role in driving adaptive responses to infection remains largely unknown. We performed low- and high-dose *T. muris* infections of mice deficient in defined cDC subsets to investigate their role in induction of adaptive immune responses. Mice lacking IRF4-dependent cDC failed to clear a high-dose infection and displayed impaired Th2 responses. Conversely, mice lacking IRF8-dependent cDC cleared a low-dose infection and displayed an impaired Th1 response while increased production of Th2 cytokines. Finally, mice lacking both IRF4- and IRF8-dependent cDC were able to generate a Th2 response and clear a low-dose infection. Collectively, these results suggest that IRF4- and IRF8-dependent cDC act antagonistically during *T. muris* infection, and demonstrate that intestinal Th2 responses can be generated towards *T. muris* in the absence of IRF4-dependent cDC.

KEYWORDS
dendritic cells, infection, intestine, mesenteric lymph nodes, parasite, T helper cells

1 | BACKGROUND

*Trichuris muris* (*T. muris*) is the murine counterpart to the human parasitic nematode *T. trichiura* that infects almost 500 million people in tropical regions.1 *T. muris* larvae invade the caecal epithelium upon hatching and give rise to acute or chronic infections depending on the nature of the adaptive immune response. Hence, chronic infections, defined by the presence of worms at day 35 post-infection (p.i.), are tightly associated with Th1 responses, while clearance of infection prior to the worms reaching fecundity is dependent on generation of a Th2 response.2 This balance, and the subsequent outcome of the infection, is influenced by differences in genetic background, infection dose and gender.3 This is particularly evident in C57BL/6 mice, where a high-dose infection stimulates a Th2 response and clearance, while a low-dose infection results in a Th1 response and chronicity.2 Production of the Th1-associated cytokines IL-12 and IFN-γ is critical for establishment of chronic *T. muris* infection. Thus, neutralization of IFN-γ in normally susceptible AKR mice results in expulsion of *T. muris* worms,4 while resistant mice become susceptible and display increased worm burden upon IL-12 administration.5

Classical dendritic cells (cDC) play a central role in the induction and regulation of adaptive T helper cell responses. The intestinal mucosa contains several cDC subsets that are subdivided based on their expression of the integrins CD11b and CD103 into CD103+CD11b− (CD103 SP), CD103+CD11b+ (DP) and CD103−CD11b+ (CD11b SP) cDC.6 The development of intestinal CD103 SP cDC is dependent on the transcription factors IRF8, BATF3 and ID2,7–10 while lack of IRF4 or Notch2 results in a loss of DP cDC and reduced numbers of CD11b SP cDC in intestinal-draining MLN.11–14 We have previously demonstrated that mice lacking IRF8-dependent cDC have dramatically reduced numbers of intestinal Th1 cells and fail to support Th1 responses to immunized protein antigen in MLN.7 In contrast, mice deficient in IRF4-dependent cDC have reduced numbers of intestinal Th17 cells11 and fail to mount Th2...
responses to helminth infection, or immunization with allergens or parasite-derived antigens, in the respiratory tract, skin and intestinal mucosa. While CD accumulation in the intestinal mucosa and MLN of T. muris-infected mice, the role of intestinal cDC subsets in the induction of T cell responses, and the interplay between these subsets in determining infection outcome, remains limited. In this study, we assessed the role of MLN cDC subsets in high- and low-dose T. muris infection and the potential synergistic or antagonistic role these subsets play during infection.

2 | MATERIALS AND METHODS

2.1 | Mice

C57BL/6, CD11c-cre::IRF4fl/fl or Flt3L and CD11c-cre::IRF4fl/fl (IRF8fl/fl) were generated, bred and maintained at the Biomedical Center (BMC), Lund University, or at the quarantine at Medicin Village, Lund University, as previously described. Cre-negative IRF4IRF8fl/fl or IRF8IRF8fl/fl littersmates were used as controls. Cre-expressing litterers with either flox/flox or flox/- genotype displayed the same phenotype and were combined for all experiments. For generation of bone marrow (BM) chimeras, irradiated recipient mice (CD45.1+; 900 cGy) were reconstituted with BM cells (~1 x 10^6 cells) from indicated donor mice (CD45.2+) by i.v. injection within 24 hours of irradiation. Infection with T. muris eggs was performed 7-8 weeks after reconstitution. The donor cells constituted >95% of the cells within the DC compartment in both groups of chimeric mice (Cre- mice: average 97.5% ± 2.1% [n = 7]; Cre+ mice: average 99.8% ± 0.2% [n = 5]) (Fig. S2). All experimental procedures were performed in strict accordance with ethical permission granted by the Malmö/Lund Animal Ethics Committee.

2.2 | Trichuris muris

Mice were infected by oral gavage with approximately 30-40 or 250-300 infective T. muris eggs (E isolate) for low- and high-dose infections, respectively. Parasite-derived excretory/secretory (E/S) antigens were collected from secreting worms after 4 hours. To assess worm burden, large intestinal and caecal tissue were carefully scraped and worms counted under a microscope.

2.3 | Cell isolation, in vitro stimulations and cytokine analyses

MLN cells were isolated according to standard procedure. For E/S antigen re-stimulation, ~1 x 10^6 MLN cells were suspended in 100 μL RPMI1640 supplemented with 10% foetal calf serum (Sigma-Aldrich, Stockholm, Sweden), 1 mM sodium pyruvate (Gibco), 10 mM HEPES, 100 U/mL penicillin and 100 μg/mL streptomycin, and 50 μM 2-mercaptoethanol (Gibco), and cultured with 50 μg/mL E/S antigens for 48 hours at 37°C, 5% CO2, in a 96-well U-bottomed plate. Cell-free supernatants were subjected to cytokine analysis using cytomectric bead arrays (BD Biosciences), according to manufacturer’s instructions. Samples were acquired on a BD Accuri C6 Flow cytometer Sampler (BD Biosciences) and data analysed with FCAP Array v3.0 (SoftFlow Inc.).

For analysis of intracellular cytokines, MLN cells were stimulated in a 96-well plate with PMA (Sigma-Aldrich; 50 ng/mL) and ionomycin (Sigma-Aldrich; 500 ng/mL). Brefeldin A (Sigma-Aldrich; 10 μg/mL) and monensin (Sigma-Aldrich; 2 μg/mL) were added after 1 hour of culture, and the cells harvested three hours later, followed by flow cytometry analysis.

2.4 | Flow cytometry

Cells were stained for flow cytometry analysis of surface marker expression and intracellular cytokine production according to standard procedures. Briefly, cells were surface-stained with indicated antibodies (Table S1) at 4°C for 20 minutes. Intracellular staining was performed on fixed and permeabilized cells at room temperature for 45 minutes, according to manufacturer’s instructions (FoxP3 Transcription factor staining buffer set; eBioscience). Dead cells were excluded by staining with propidium iodide or Violet Live/Dead (Life Technologies), according to manufacturer’s instructions. Data were acquired on a BD LSR II flow cytometer and analysed using FlowJo software v9.6.2 (Tree Star).

2.5 | Statistical analyses

Statistical analyses were performed using GraphPad Prism software (GraphPad); significance was determined with Mann-Whitney U test or Kruskal-Wallis test followed by Dunns’s post-test (as indicated in Figure legends).

3 | RESULTS

3.1 | Investigation of MLN cDC composition during Trichuris muris infection

To investigate the MLN cDC subset composition during acute and chronic T. muris infection, C57BL/6 mice were infected with a high (250-300) and low (30-40) egg dose, respectively. Analysis of the cDC subset composition in the MLN was performed at day 7 p.i., as previous publications have demonstrated that T. muris-specific cytokine responses can be detected in the MLN from approximately day 10 p.i.22 22 cDC in the MLN can be subdivided into MHC-IIhi and MHC-IIint cells, with the former representing intestinal-derived migratory cDC, and the latter lymph node-resident cDC.24 Migratory MHC-IIhi MLN cDC consist of CD103 SP, DP and CD11b SP cDC, while resident MHC-IIint MLN cDC can be subdivided into CD11b+ and CD11b- cells (gating strategy in Fig. S1).24 Both high- and low-dose T. muris infection led to a significant increase in MLN cellularity at day 7 p.i. (Fig. S1). Total cDC (CD11c+ MHC-II+) numbers also increased in the MLN during high, but not low-dose infection (Figure 1B), which included an increase in both MHC-IIhi and MHC-IIint cDC (Figure 1B). After high-dose infection, there was a significant increase in the numbers of DP and CD11b SP, but not
CD103 SP MHC-II^hi cDC, as well as CD11b^+ and CD11b^- MHC-II^int cDC (Figure 1C). Taken together, these data suggest that cDC accumulate in MLN at day 7 p.i. preferentially during high-, but not low-, dose infection with *T. muris*.

To investigate whether IRF4 and IRF8 expression was altered in cDC during infection, we analysed intracellular expression of IRF4 and IRF8 in MLN cDC subsets at day 7 after high- and low-dose *T. muris* infection. Consistent with previous reports, IRF4 and IRF8 were expressed selectively by DP and CD103 SP cDC, respectively, in uninfected mice (Figure 1D,E). Furthermore, we detected no alterations in IRF4 and IRF8 expression levels following high- or low-dose infection (Figure 1E). Therefore, we conclude that MLN cDC subsets maintain their selective pattern of IRF4 and IRF8 expression during *T. muris* infection.

### 3.2 | IRF4-dependent cDC are critical for induction of adaptive Th2 responses during *Trichuris muris* infection

Mice with a selective deletion of IRF4 in the CD11c-compartment (CD11c-cre:IRF4^fl/fl or IRF4^cre/mice) have a strong reduction of migratory DP cDC and a twofold reduction of migratory CD11b SP cDC in the MLN. We have recently shown that CD11c-cre:IRF4^fl/fl mice infected with a high-dose of *T. muris* become chronically infected and display reduced Th2 responses at day 35 p.i. To further examine the role of IRF4-dependent cDC in response to *T. muris* infection at a time point when the infection is still ongoing in both mouse strains and coinciding with the peak cytokine response, CD11c-cre:IRF4^fl/fl or IRF4^fl/fl control mice were infected with a high egg dose followed by analysis at day 21 p.i. Interestingly, total...
MLN cellularity, total numbers of cDC and total numbers of MHC-IIhi and MHC-IIint cDC were higher in CD11c-cre.IRF4fl/- or fl/fl mice compared with control mice (Figure 2A). As previously observed in the steady state,11 migratory DP cDC were absent in the MLN of T. muris-infected CD11c-cre.IRF4fl/- or fl/fl mice (Figure 2B and C). The increase in MHC-IIhi cDC in the MLN of CD11c-cre.IRF4fl/- or fl/fl mice was due to an enhanced accumulation of migratory CD11b SP and CD103 SP cDC (Figure 2C). In addition, both CD11b+ and

![Graphs and plots](image-url)
CD11b+ MHC-II^int cDC subsets were increased in CD11c-cre.IRF4<fl/- or fl/fl mice (Figure 2C). Furthermore, CD11c-cre.IRF4<fl/- or fl/fl mice retained a significantly higher number of worms compared to control mice (Figure 2D). Given the time point of analysis (day 21 p.i.), these results suggest ongoing but not completely worm expulsion in control, but not CD11c-cre.IRF4<fl/- or fl/fl mice. In line with these results, we observed reduced IL-13 production by MLN cells from CD11c-cre.IRF4<fl/- or fl/fl mice after re-stimulation with T. muris-derived E/S antigens, with similar trends for IL-9 and IL-5 (Figure 2E). Furthermore, while the frequency of CD44+ cells in the CD4+ MLN T cell population did not differ between the two groups (Figure 2F), CD11c-cre.IRF4<fl/- or fl/fl mice contained a significantly decreased proportion of IL-13-producing CD4+ CD44+ T cells and an increased frequency of IFN-γ-producing CD4+ CD44+ T cells after polyclonal re-stimulation (Figure 2F,G). Taken together, these results demonstrate that CD11c-cre.IRF4<fl/- or fl/fl mice have impaired capacity to mediate worm expulsion and induce Th2 cells in the MLN following high-dose T. muris infection. Furthermore, the increased number of IFN-γ-producing CD4+ cells in CD11c-cre.IRF4<fl/- or fl/fl mice may indicate that IRF4-dependent cDC, potentially through their ability to drive Th2 responses, curtail the Th1 response to T. muris infection.

3.3 | CD11c-cre.IRF8<fl/- or fl/fl mice infected with a low dose of Trichuris muris eggs expel worms and display an increased Th2 response

We recently demonstrated that mice that lack IRF8-dependent cDC, in contrast to wild-type control mice, are able to clear a low-dose T. muris infection. Given the importance of Th1 cells for the establishment of chronic T. muris infection, we therefore assessed the generation of Th1 cells in CD11c-cre.IRF8<fl/- or fl/fl mice following low-dose infection. MLN cellularity, total numbers of cDC, and MHC-II^int and MHC-II^hi cDC did not differ between CD11c-cre.IRF8<fl/- or fl/fl and control IRF8<fl/fl mice at day 18 p.i. (Figure 3A). Consistent with previous results in the steady state, infected CD11c-cre.IRF8<fl/- or fl/fl mice completely lacked migratory CD103+ cDC and had an increased number of resident CD11b+ cDC in the MLN (Figure 3B,C), while the total numbers of migratory DP and CD11b SP cDC, and resident CD11b- cDC, remained unchanged (Figure 3C). Furthermore, while worms were still present in control mice, CD11c-cre.IRF8<fl/- or fl/fl mice showed near complete worm expulsion already by day 18 p.i. (Figure 3D), consistent with our previous analysis at day 35 p.i. To determine whether CD11c-cre.IRF8<fl/- or fl/fl mice display an altered immune response to T. muris infection, we assessed production of Th1 and Th2 cytokines by MLN cells. The numbers of IFN-γ-producing CD4+ CD44+ T cells after polyclonal stimulation at day 18 and 35 p.i. were dramatically reduced in CD11c-cre.IRF8<fl/fl mice compared with IRF8<fl/fl mice (Figure 3E). Strikingly, low-dose infection induced a strong Th2 response in CD11c-cre.IRF8<fl/fl, but not in control IRF8<fl/fl mice, as evidenced by marked elevation in IL-4, IL-5, IL-9 and IL-13 levels in MLN cell suspensions re-stimulated with E/S antigens (Figure 3F). Collectively, these results suggest that IRF8-dependent cDC may serve to limit T. muris-specific Th2 responses during low-dose infection, and that their absence results in Th2-mediated worm expulsion.

3.4 | CD11c-cre.IRF4<fl/- or IRF8<fl/fl BM chimeric mice infected with a low dose of Trichuris muris expel worms and display an elevated Th2 response

Given the key role of IRF4- and IRF8-dependent cDC in driving adaptive Th2 and Th1 responses to T. muris, respectively, and our results suggesting that these subsets antagonize one another’s function during T. muris infection, we next assessed how mice lacking both IRF4 and IRF8 in their CD11c-compartment would respond to a low-dose T. muris infection. In preliminary experiments, we first examined the MLN cDC composition of CD11c-cre.IRF4<fl/- or fl/fl and littermate control (IRF4<fl/- or fl/fl,IRF8<fl/fl) mice. The total number of MLN cells was higher in uninfected CD11c-cre.IRF4<fl/- or fl/fl,IRF8<fl/fl mice compared with littermate controls; however, no differences in MLN cell number were observed at day 21 p.i. (Fig. S2AB), while total CD11c cDC numbers were similar between CD11c-cre.IRF4<fl/- or fl/fl,IRF8<fl/fl and littermate controls in steady state and at day 21 p.i (Fig. S2AB). In contrast, migratory MHC-II^int MLN cDC were strongly decreased and lymph node-resident MHC-II^int cDC increased in both infected and uninfected CD11c-cre.IRF4<fl/- or fl/fl,IRF8<fl/fl mice (Fig. S2B,C). A decrease in migratory cDC numbers was observed for both CD103 SP and DP cDC, while CD11b SP cDC were increased in uninfected mice but reduced after infection (Fig. S2D,E). Within the lymph node-resident MHC-II^int cDC population, there was an increased number of CD11b+ cDC (Fig. S2B,E). Strikingly, despite the absence of both IRF4- and IRF8-dependent cDC, CD11c-cre.IRF4<fl/- or fl/fl,IRF8<fl/fl mice had expelled T. muris larvae already at day 21 p.i. (Fig. S2F).

As insufficient numbers of CD11c-cre.IRF4<fl/- or IRF8<fl/fl mice were available for further analyses, due to major breeding issues, and to further extend the preliminary analyses in CD11c-cre.IRF4<fl/- or fl/fl,IRF8<fl/fl mice, we next assessed the nature of adaptive immune responses to T. muris infection in the absence of IRF4- and IRF8-dependent cDC, by generating BM chimeric CD11c-cre.IRF4<fl/- or fl/fl,IRF8<fl/fl mice, respectively. While the total number of MLN cells and cDC was similar in both groups of BM chimeric mice upon analysis at day 21 p.i. (Figure 4A,B), CD11c-cre.IRF4<fl/- or fl/fl,IRF8<fl/fl mice showed near complete worm expulsion already by day 18 p.i. (Figure 4C, consistent with our previous observation in infected and uninfected CD11c-cre.IRF4<fl/- or fl/fl,IRF8<fl/fl mice (Fig. S2C). Furthermore, while the total number of resident cDC was similar between the groups (Figure 4C), the proportion of CD11b+ cells within this population was increased in CD11c-cre.IRF4<fl/- or fl/fl,IRF8<fl/fl mice (Figure 4D). Moreover, chimeric CD11c-cre.IRF4<fl/- or fl/fl,IRF8<fl/fl mice, but not control IRF4<fl/fl,IRF8<fl/fl BM chimeras, were capable of mediating worm expulsion by day 21 p.i. (Figure 4E). To assess the nature of the immune response to infection, we analysed Th1 and Th2 cytokine production by MLN cells. In contrast to control BM chimeras, E/S antigen-stimulation of MLN cells from CD11c-cre.IRF4<fl/- or fl/fl,IRF8<fl/fl BM chimeras resulted in Th2 cytokine production (Figure 4F). In contrast, IFN-γ-producing CD4+ CD44+ T cells were readily detected in the MLN of IRF4<fl/-,IRF8<fl/fl, but
not in CD11c-cre:IRF8fl/fl:IRF8fl/fl BM chimeras (Figure 4G). Thus, despite previous studies suggesting a critical role for IRF4-dependent cDC in the induction of Th2 responses, additional APC subsets appear capable of driving Th2 immunity to T. muris infection in mice with a combined deficiency in IRF4- and IRF8-dependent cDC.

**DISCUSSION**

Adaptive immune responses to infection with the large intestinal nematode T. muris can be polarized into either Th1 or Th2 responses, depending on the infection dose and genetic background of the mice.26
However, despite its widespread use as a model to study intestinal adaptive immune responses, the role of cDC in induction of Th1 and Th2 responses to *T. muris* infection remains incompletely characterized. Consistent with previous studies, we demonstrate here that induction of Th1 and Th2 responses during low- and high-dose infection with *T. muris* is mediated by IRF8- and IRF4-dependent cDC, respectively. Interestingly, the absence of IRF8-dependent cDC, and the associated failure to induce Th1 cells, during low-dose infection resulted in a dramatic increase in Th2 cytokines and worm expulsion. Finally, we show that Th2 responses to *T. muris* can develop in the absence of IRF4-dependent cDC, when IRF8-dependent cDC and associated Th1 responses are not present. Collectively, these results suggest a complex and antagonistic interplay between cDC subsets in the generation and regulation of *T. muris*-specific Th cell responses.

We have previously demonstrated that mice deficient in IRF8-dependent cDC clear low-dose *T. muris* infection prior to day 35 p.i., and that this is associated with an inability to generate *T. muris*-specific IgG2c. Switching to IgG2a as well as establishment of chronic *T. muris* infection, is associated with IFN-γ-producing CD4+ T cells, and we demonstrate here that in the absence of IRF8-dependent cDC, *T. muris*-specific IFN-γ-responses are markedly reduced. Such findings are consistent with our prior observations that IRF8-dependent cDC are essential for the establishment/maintenance of intestinal Th1 cells during homeostasis. Strikingly, Th2 responses were dramatically increased in the absence of IRF8-dependent cDC, suggesting that in addition to generating Th1 responses, IRF8-dependent cDC may serve to antagonize Th2 responses during *T. muris* infection. A plausible mechanism by which IRF8-dependent cDC counteract *T. muris*-specific Th2 responses could be through their constitutive production of IL-12, as recently suggested during *Schistosoma mansoni* infection. IL-12 is known to play a critical role in establishing chronic *T. muris* infection in an IFN-γ-dependent manner; however, whether IL-12 can also impact directly on Th2 responses during *T. muris* infection is yet to be investigated. Interestingly, mice that lack the TGFβ-activating integrin αvβ8 selectively in the CD11c-compartment display enhanced Th2 responses following low-dose *T. muris* infection compared to wild-type mice, resulting in worm expulsion. Furthermore, we have recently demonstrated that αvβ8 is selectively expressed by CD103+CD11b- BM chimeric mice. Thus, an alternative possibility for why an absence of IRF8-dependent DCs results in enhanced Th2 responses is that these cells selectively generate the active form of TGFβ, which may be involved in negatively regulating Th2 responses. Finally, although less dramatic, our results also indicated a potential role of IRF4-dependent cDC in antagonizing Th1 responses, as IFN-γ was increased in the absence of these cells, associated with failure to clear the infection. Together, these results suggest an important interplay between cDC subsets in the regulation of adaptive T helper cell responses during *T. muris* infection.

We recently demonstrated that IRF4-dependent cDC play a critical role in production of Th2 cytokines during high-dose *T. muris* infection, and that mice deficient in IRF4-dependent cDC become chronically infected. Consistent with these results, we show here that mice lacking IRF4-dependent cDC failed to induce Th2 cells after high-dose infection and displayed delayed worm expulsion. Given these results,
surprisingly, mice with a combined deficiency in both IRF4- and IRF8-dependent cDC, which as a consequence have a strong reduction in migratory MLN cDC, responded to low-dose T. muris infection by production of Th2 cytokines and expulsion of the larvae. It remains unclear how Th2 responses can be generated in the absence of migratory IRF4-dependent cDC. One possibility is that parasite-derived antigens reach the MLN via the lymphatic drainage in the absence of migratory cDC to be taken up and presented by the remaining cDC in the MLN. The dominating cDC subsets in the MLN of infected CD11c-cre:IRF4fl/fl,IRF8fl/fl mice consisted of resident CD11b+ MHC-II+ cDC. While the role of these cells in the generation of Th2 responses has not been investigated, it is plausible that they are capable of driving Th2 responses in the absence of IRF8-dependent cDC. Furthermore, although strongly reduced in number, we did observe a population of residual migratory cDC in the MLN of T. muris-infected CD11c-cre:IRF4fl/fl or IRF8fl/fl mice. Thus, we cannot rule out that these cells may contribute to the Th2 responses detected in the MLN of CD11c-cre:IRF4fl/fl,IRF8fl/fl mice. Alternatively, while cDC are the critical antigen-presenting cells during induction of Th2 responses under normal conditions,31,32 other cells may compensate for the lack of migratory IRF4- and IRF8-dependent cDC. In this respect, a variety of innate immune cell types have previously been suggested to present antigen to induce Th2 responses, including basophils,33–35 eosinophils36–39 and ILCs.40,41 While these cells are preferentially thought to play accessory roles during the initial phase of Th2 responses, it is plausible that they take more active part in antigen presentation in the absence of migratory cDC, in particular IRF8-dependent cDC. Together, our data demonstrate that although IRF4-dependent cDC induce adaptive Th2 and Th1 responses, respectively, during high- and low-dose T. muris infection, in line with previous studies.15–18 Importantly, we also demonstrate an antagonistic interplay between IRF4- and IRF8-dependent cDC subsets in the regulation of Th helper cell responses, and finally, that IRF4-dependent cDC can be redundant for induction of Th2 responses, at least in the concurrent absence of IRF8-dependent cDC.

ACKNOWLEDGMENTS

We are thankful to Dr D. Sorobetea and Dr T. Joeris for critical comments to the manuscript. This work was supported by grants from The Swedish Research Council, Crafoord Foundation, Carl Trygger Foundation, Per-Eric and Ulla Schyberg’s Foundation, and the Foundation Sigurd and Elsa Goljes Minne.

CONFLICT OF INTEREST

The authors declare no conflict of interests.

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REFERENCES


SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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