Mycobacterium tuberculosis infection induces il12rb1 splicing to generate a novel IL-12Rβ1 isoform that enhances DC migration

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In the original version of this article, an error appeared the running title. The correct running title is as follows: Splicing of il12rb1 alters DC migration. The error has been corrected in the pdf version of the article.
Mycobacterium tuberculosis infection induces il12rb1 splicing to generate a novel IL-12Rβ1 isoform that enhances DC migration

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RNA splicing is an increasingly recognized regulator of immunity. Here, we demonstrate that after Mycobacterium tuberculosis infection (mRNA) il12rb1 is spliced by dendritic cells (DCs) to form an alternative (mRNA) il12rb1 tm that encodes the protein IL-12Rβ1ΔTM. Compared with IL-12Rβ1, IL-12Rβ1ΔTM contains an altered C-terminal sequence and lacks a transmembrane domain. Expression of IL-12Rβ1ΔTM occurs in CD11c+ cells in the lungs during M. tuberculosis infection. Selective reconstitution of il12rb1−/− DCs with (mRNA) il12rb1 and/or (mRNA) il12rb1 tm demonstrates that IL-12Rβ1ΔTM augments IL-12Rβ1-dependent DC migration and activation of M. tuberculosis-specific T cells. It cannot mediate these activities independently of IL12Rβ1. We hypothesize that M. tuberculosis-exposed DCs express IL-12Rβ1ΔTM to enhance IL-12Rβ1-dependent migration and promote M. tuberculosis-specific T cell activation. IL-12Rβ1ΔTM thus represents a novel positive-regulator of IL12Rβ1-dependent DC function and of the immune response to M. tuberculosis.

The control of M. tuberculosis infection occurs through an acquired antigen–specific CD4+ T cell response and the IL12B gene is essential to this response (Cooper et al., 2007; Cooper, 2009). Although IL-12 plays an expected role in modulating Th1 responses to M. tuberculosis, we have also shown that IL-12(p40)2 is required for DCs to migrate in response to chemokines after exposure to mycobacterial and other pathogenic stimuli (Khader et al., 2006; Robinson et al., 2008). That this migration may be important in initiating T cell responses is suggested by the observation that depletion of CD11c+ cells before infection delays T cell activation and influences the outcome of infection (Tian et al., 2005).

IL-12 family members mediate their biological activities through specific, high-affinity dimeric receptors. All these receptors share IL-12Rβ1, a 100-kD glycosylated protein that spans the plasma membrane and serves as a low-affinity receptor for the IL-12p40 subunit of IL-12 family members (Chua et al., 1994, 1995; coexpression with IL-12Rβ2 or IL-23R results in high-affinity binding of IL-12 and IL-23, respectively, and confers biological responsiveness to these cytokines (Presky et al., 1996; van Rietschoten et al., 2000; Parham et al., 2002). Polymorphisms in IL12B or IL12RB1 are associated with psoriasis (Capon et al., 2007), atopic dermatitis, and other allergic phenotypes (Takahashi et al., 2005) and, importantly, nonfunctional IL12RB1 alleles...
predispose to mycobacterial susceptibility (Altare et al., 1998; de Jong et al., 1998; Filipe-Santos et al., 2006; Fortin et al., 2007). Thus, understanding how IL-12Rβ1 expression and IL-12Rβ1–dependent signaling is regulated has important implications for tuberculosis and may impact other diseases.

Given that CD11c+ cells contribute to the control of M. tuberculosis infection (Tian et al., 2005) and that IL-12(p40)/IL-23 is required for their migration in response to pathogenic stimuli (Khader et al., 2006; McCormick et al., 2008; Robinson et al., 2008), we sought to determine if IL-12Rβ1 is required for DC migration after exposure to this organism. In the course of these investigations we not only confirmed this hypothesis but also discovered that DCs express both IL-12Rβ1 and a novel IL-12Rβ1 splice variant (IL-12Rβ1ΔTM) in response to M. tuberculosis. This splice variant can be seen at the mRNA level in CD11c+ cells from the lungs of M. tuberculosis–infected mice and as a protein in the membrane of DCs. Importantly, we have determined that IL-12Rβ1ΔTM functions to enhance IL-12Rβ1–dependent DC migration and promote CD4+ T cell activation. This finding not only impacts our understanding of DC migration and IL-12Rβ1–dependent mycobacterial immunity it also reveals a previously unknown positive regulator of IL-12Rβ1–dependent events.

RESULTS

IL-12Rβ1 is required for M. tuberculosis–induced DC migration and function

As il12b is required for DC migration in response to M. tuberculosis (Khader et al., 2006), it was necessary to determine whether il12rb1, which encodes the receptor for IL-12β (Presky et al., 1998; Wang et al., 1999; Oppmann et al., 2000), is expressed by DCs in response to M. tuberculosis and if it is required for subsequent DC migration and T cell priming. To do this, we delivered M. tuberculosis via the intratracheal route and found that the frequency of CD11c+ cells expressing IL-12Rβ1 in the lungs increases 3 h after delivery (Fig. 1 A); BM-derived DCs (BMDCs) also respond to M. tuberculosis by increasing the expression of IL-12Rβ1 on CD11c+ cells (Fig. 1 B). To test if il12rb1 was required for DC migration after mycobacterial stimulation, we generated an immature population of il12rb1−/− BMDCs and tested its ability to migrate toward the homeostatic chemokine CCL19 using a previously established method (Khader et al., 2006). il12rb1−/− DCs are morphologically and phenotypically similar to C57BL/6 DCs (unpublished data); however, in an in vitro transwell assay, il12rb1−/− DCs had a significantly lower migratory response toward CCL19 after exposure to varying

![Image](99x181 to 519x427)

Figure 1. IL-12Rβ1 is required for M. tuberculosis–induced DC migration. (A) M. tuberculosis was instilled into the trachea of C57BL/6 mice, and 3 h later the frequency of CD11c+IL-12Rβ1+ cells in the lungs was determined. Dot plots are representative of four mice per condition; this experiment was performed twice with two separate BM preparations. (B) C57BL/6 BMDCs were exposed to M. tuberculosis or media alone, and 3 h later the frequency of CD11c+IL-12Rβ1+ cells was determined. Dot plots represent the same BMDC preparation stimulated with either condition and are representative of three separate experiments. (C) BMDCs generated from C57BL/6 or il12rb1−/− mice were assayed for their ability to migrate to CCL19 in a transwell assay after a 3-h exposure to M. tuberculosis (CI, number moved in response to CCL19/number moved to media alone). Data points in C represent mean and SD of triplicate values and are representative of three separate experiments; for the difference between CI induced in C57BL/6 relative to il12rb1−/− DCs, *, P < 0.05; **, P < 0.005, as determined by Student's t test. (D–F) M. tuberculosis/CFSE was instilled via the trachea into C57BL/6, il12b−/−, il12rb1−/−, or il12rb2−/− mice. 18 h later, the frequency (D and E) and total number of CD11c+CFSE+ cells in the draining MLN were counted. The data points in E and F represent the mean and SD of combined data from four mice per group (F) and are representative of two separate experiments; for the difference between percentage and/or number of CD11c+CFSE+ cells found in C57BL/6 mice relative to il12b−/− or il12rb1−/− mice, *, P < 0.05; **, P < 0.0005, as determined by Student's t test.
concentrations of *M. tuberculosis* compared with C57BL/6 controls (Fig. 1 C). To determine if this was also true in vivo, we administered a mixture of *M. tuberculosis* and CFSE to *il12b−/−, il12b1−/−, il12hb−/−*, and C57BL/6 mice via the trachea and the number of CFSE+ CD11c+ cells in the draining mediastinal LN (MLN) was determined 18 h later. Although nonmanipulated mice of all genotypes had similar amounts of CD11c+ cells in their lung and MLN (not depicted), we consistently observed a lower frequency (Fig. 1, D and E) and fewer numbers (Fig. 1 F) of CD11c+CFSE+ cells in the MLN of *il12b−/−* and *il12rb1−/−* mice after administration via the trachea of *M. tuberculosis* and CFSE. This was not true of *il12rb2−/−* mice, further supporting a role for IL-12(p40)2, and not IL-12p70, in DC migration (Khader et al., 2006). These results demonstrate that *il12rb1* is required for *M. tuberculosis*–induced CD11c+ cell migration from the lung to the draining MLN.

A reduced frequency of *il12rb1*-sufficient CD11c+ cells in the lung delays the activation of *M. tuberculosis*-specific T cells

CD4+ T cell responses to *M. tuberculosis* antigens are initiated in the MLN (Gallegos et al., 2008; Reiley et al., 2008; Winslow et al., 2008; Wolf et al., 2008). Therefore, we speculated that a delay in CD11c+ cell migration would delay the activation of *M. tuberculosis*-specific CD4+ T cells. To test this idea, we used diphtheria toxin (DT) to specifically deplete *il12rb1+/*CD11c+ cells from BM chimeras that contained DT receptor–positive (DTR+) C57BL/6 CD11c+ cells and DTR-negative *il12rb1−/−*CD11c+ cells and measured *M. tuberculosis*-specific T cell activation to intratracheal administration of *M. tuberculosis* and antigen. The chimeras were generated by reconstituting lethally irradiated C57BL/6 mice with 25% *il12rb1−/−* and 75% *Ilgax-DTR/eGFP* BM (DTR:*il12rb1−/−* mice) or, as a control, 25% C57BL/6 and 75% *Ilgax-DTR/EGFP* BM (DTR:WT mice). The *Ilgax-DTR/eGFP* mice are transgenic for a simian DTR fused to an enhanced GFP (eGFP) that is under control of the *Ilgax* (or CD11c) promoter. Upon DT administration, CD11c+ cells containing this transgene are transiently depleted in most tissues (Jung et al., 2002).

In control DTR:WT mice injected with saline, the majority of CD11c+ cells are GFP+, demonstrating reconstitution of the lung with DTR-expressing cells (Fig. 2 A).
Both GFP+ and the subset of GFP− CD11c+ cells are il12b1+/+ and express basal levels of IL-12Rβ1 on their surface (Fig. 2 A). Upon injection of DT, the frequency of GFP+ CD11c+ cells drops ∼12-fold (Fig. 2 B), resulting in an increased ratio of GFP− to GFP+ CD11c+ cells. Treating the DTR-il12b1−/− mice with DT resulted in a similar drop in GFP− CD11c+ cells (Fig. 2, F and G), and therefore a greatly reduced frequency of il12b1−/− CD11c+ cells in the lungs of these mice.

To compare the relative T cell–activating ability of lungs harboring a high frequency of il12b1+/+ CD11c+ cells to those with a low frequency, we measured the response of antigen-specific cells in the MLN. To do this, we intravenously transferred 1.5 × 10⁶ CFSE-labeled ESAT-specific T cells (Fig. 2, C and H) expressing markers of activation CD69 (Fig. 2, D and I) and CD44 (Fig. 2, E and J) in the draining MLN was determined. The frequency of ESAT6-specific T cells that expressed a high level of CD44 (Fig. 2 K) and CD69 (Fig. 2 L) in response to two different doses of antigen within the 18 h of the experiment was significantly lower in the mice with a reduced frequency of il12b1+/+ CD11c+ cells. Thus, an increase in the ratio of il12b1−/− to il12b1+/+ DCs in the lungs is associated with impaired activation of antigen-specific T cells in the draining MLN. These data demonstrate that il12b1+ expression in CD11c+ cells within the lungs is required for M. tuberculosis–induced DC migration and induction of T cell activation in vivo.

IL-12(p40)2 initiates nuclear accumulation of NF-κB in DCs

We wished to better understand the mechanism by which IL-12Rβ1–dependent signaling modulates DC chemotaxis after exposure to M. tuberculosis. Lower levels of CCR7 (the receptor for CCL19) do not account for this result, as surface expression of CCR7 is similar between activated WT and il12b1−/− BMDCs (unpublished data). To determine if any intracellular signaling pathways that influence DC migration were altered in il12b1−/− DCs, we measured the phosphorylation levels of NF-κB, SAPK/JNK, p38α MAP kinase, and STAT3 in these cells after stimulation with M. tuberculosis. We observed that stimulation of C57BL/6 DCs increases phospho-NF-κB levels above those of unstimulated controls (Fig. 3, A and B). However, we consistently observed that levels of phospho-NF-κB were lower in il12b1−/− DCs compared with WT DCs at several time points, despite equivalent levels of total NF-κB (Fig. 3, C and D). No differences in phospho-SAPK/JNK, p38α MAP kinase, and STAT3 were observed between WT and il12b1−/− DCs (unpublished data). These data suggest that NF-κB–dependent processes are compromised in il12b1−/− DCs.

Because NF-κB phosphorylation was defective in il12b1−/− DCs, we reasoned that NF-κB binding should be enhanced when DCs are stimulated via IL-12Rβ1. To test this hypo-

Figure 3. NF-κB signaling is impaired in il12b1−/− DCs and can be promoted by IL-12(p40)2. (A–D) BMDCs generated from C57BL/6 and il12b1−/− mice were exposed to M. tuberculosis (B and D) or media alone (A and C) for the indicated times. After this period, cells were harvested under non-denaturing conditions and levels of total NF-κB p65 (open bars) and phospho-NF-κB p65 (closed bars) were determined by ELISA. Shown are the light absorbance values (A_{450}) from one experiment that is representative of two experiments with separate BMDC preparations. (E) BMDCs were generated from il12b1−/− mice and exposed to media alone, M. tuberculosis, IL-12(p40)2, or both M. tuberculosis and IL-12(p40)2. 1 h later, nuclear extracts of the treated cells were isolated and EMSA of NF-κB consensus sequence–binding proteins was performed. Shown is a blot of NF-κB p65 consensus sequence–binding proteins from DCs stimulated with media alone (lanes 1 and 2), M. tuberculosis (lanes 3 and 4), both M. tuberculosis and IL-12(p40)2 (lanes 5 and 6), or IL-12(p40)2 alone (lanes 7 and 8). The absence (−) or presence (+) of a cold NF-κB consensus probe was used to determine the specificity of each band.
The mouse *il12rb1* gene is located on autosomal chromosome 8 and comprises 16 exons (Fig. 4 A; NCBI protein database accession no. 16161). Upon transcription and intron removal, exons 1–13 are translated into the extracellular portion of the IL-12Rβ1 protein, whereas exon 14 and exons 15–16 are translated into the transmembrane and intracellular portions, respectively (Fig. 4 B). To determine the transcription activity of this gene in DCs, we amplified cDNA from BMDC cultures with a variety of primers spanning different lengths of (cDNA) *il12rb1* (Fig. 4 B). Amplification with primers (P) recognizing the extracellular-encoding region (P1–P2) resulted in an amplicon (Fig. 4 C; cDNA from concanavalin-A–activated splenocytes is used as a positive control). Amplification of a more 3′ region with primers P3–P5 also resulted in a PCR product in both unstimulated and stimulated DCs; however, under these amplification conditions a second smaller band was also observable, but only in DCs that had been stimulated with *M. tuberculosis* (Fig. 4 C, arrow). This second band does not appear upon amplification with primers that span the transmembrane-encoding region (P3–P4). Sequencing both the larger and smaller band amplified by primers P3–P5 revealed that the larger product represents (mRNA) *il12rb1* and that the smaller product is identical, except for a 97-bp deletion (Fig. 4 D). This deletion has two effects: (1) deletion of the transmembrane

**BMDCs express (mRNA) *il12rb1* and an (mRNA) *il12rb1* alternative splice variant after exposure to *M. tuberculosis***

The expression of (mRNA) *il12b1* by DCs has not been universally accepted because of an inability to reproducibly detect this transcript (Grohmann et al., 1998). However, given the influence of *il12b1* on DC migration (Figs. 1 and 2), we reexamined (mRNA) *il12b1* expression in these cells. The mouse *il12b1* gene is located on autosomal chromosome 8 and comprises 16 exons (Fig. 4 A; NCBI protein database accession no. 16161). Upon transcription and intron removal, exons 1–13 are translated into the extracellular portion of the IL-12Rβ1 protein, whereas exon 14 and exons 15–16 are translated into the transmembrane and intracellular portions, respectively (Fig. 4 B). To determine the transcription activity of this gene in DCs, we amplified cDNA from BMDC cultures with a variety of primers spanning different lengths of (cDNA) *il12b1* (Fig. 4 B). Amplification with primers (P) recognizing the extracellular-encoding region (P1–P2) resulted in an amplicon (Fig. 4 C; cDNA from concanavalin-A–activated splenocytes is used as a positive control). Amplification of a more 3′ region with primers P3–P5 also resulted in a PCR product in both unstimulated and stimulated DCs; however, under these amplification conditions a second smaller band was also observable, but only in DCs that had been stimulated with *M. tuberculosis* (Fig. 4 C, arrow). This second band does not appear upon amplification with primers that span the transmembrane-encoding region (P3–P4). Sequencing both the larger and smaller band amplified by primers P3–P5 revealed that the larger product represents (mRNA) *il12b1* and that the smaller product is identical, except for a 97-bp deletion (Fig. 4 D). This deletion has two effects: (1) deletion of the transmembrane
sequence encoded by exon 14 and (2) a translational frame shift that results in an early stop codon. This translational frame shift also results in the loss of the Box1/2 signaling domains that are found in the IL-12Rβ1 protein (van de Vosse et al., 2003). Both the nucleotide and deduced amino acid sequence of this smaller band (Fig. 4E) match that of a previously reported alternative splice variant of the mouse IL-12Rβ1 transcript (Chua et al., 1995). Thus, DCs respond to *M. tuberculosis* by expressing two species of (mRNA) il12b1: a transmembrane-containing transcript (hereafter referred to as “(mRNA) il12b1”) and an alternatively spliced variant of (mRNA) il12b1 (hereafter referred to as “(mRNA) il12b1Δtm”).

**Kinetics of BMDC (mRNA) il12b1Δtm expression after exposure to *M. tuberculosis***

As (mRNA) il12b1Δtm was induced in BMDCs by *M. tuberculosis*, we wanted to quantify its expression; however, it proved difficult to design a Taqman real-time PCR probe that recognized (cDNA) il12b1Δtm and not (cDNA) il12b1. Thus, to better quantify the kinetics of (mRNA) il12b1Δtm expression relative to (mRNA) il12b1 in *M. tuberculosis*-stimulated DCs, we developed a PCR-based assay hereafter referred to as “IL-12Rβ1 spectratype analysis.” IL-12Rβ1 spectratype analysis is akin to TCR-CDR3 spectratype analysis (Panetier et al., 1993) and is described in Fig. S1. When IL-12Rβ1 spectratype analysis was applied to BMDCs, we observed a dose-dependent increase in the ratio of (mRNA) il12b1Δtm to (mRNA) il12b1 after a 3-h exposure to *M. tuberculosis* (Fig. 5A). In contrast (mRNA) il12b1 remains the dominant transcript in unstimulated DCs for up to 6 h (Fig. 5A). Western blot analysis demonstrated that IL-12Rβ1 is the dominant protein product in unstimulated cells, whereas IL-12Rβ1ΔTM increases in abundance after *M. tuberculosis* stimulation (Fig. 5B). That IL-12Rβ1ΔTM could locate in the membrane was indicated by Western blot analysis of cellular fractions (Fig. S1H). Thus, analysis of mRNA and Western blot analysis confirm that DCs increase the expression of il12b1Δtm and production of IL-12Rβ1ΔTM after exposure to *M. tuberculosis*.

To assess the specificity of (mRNA) il12b1 splicing in response to *M. tuberculosis*, we stimulated DCs with a variety of other microbial and cytokine stimuli. Specifically, DCs were stimulated with *Mycobacterium avium* and *Yersinia pestis* at an identical MOI, as well as with *M. avium* cell wall extract, *Escherichia coli* LPS, TNF, IL-12, and IL-12(p40); production of IL-12Rβ1ΔTM was subsequently assessed by IL-12Rβ1 Spectratype analysis. Both *M. avium* and *Y. pestis* were capable of activating DCs as measured by IL-12p40 production (Fig. S2A). As shown in Fig. S2B, over a 6-h incubation *M. avium* was capable of eliciting IL-12Rβ1ΔTM production with kinetics that were similar to that elicited by *M. tuberculosis*. This was also observed with *M. avium* cell wall extract (Fig. S2C). Stimulation with *Y. pestis* and purified LPS (Fig. S2, D and E) failed to generate IL-12Rβ1ΔTM over the same 6-h period. Production of IL-12Rβ1ΔTM protein was also not observed after stimulation of DCs with varying *Y. pestis* MOI (Fig. S2I). Negative results were also obtained with TNF, IL-12, and IL-12(p40)2-stimulated DCs (Fig. S2, F–H). Thus, DCs increase the expression of il12b1Δtm in response to *M. tuberculosis* and the related organism *M. avium*, but not upon stimulation with Gram-negative *Y. pestis*, purified LPS, and cytokines TNF, IL-12, and IL-12(p40)2.

**Human DCs respond to stimuli by splicing IL-12Rβ1**

After activation, human DCs increase surface expression of IL-12Rβ1 (Nagayama et al., 2000). Two isoforms of the human IL-12Rβ1 transcript are reported in publicly available databases: full-length IL-12Rβ1 (isoform 1; Swiss-Prot ID P42701-1) and a shorter isoform, missing the transmembrane domain and with an altered C-terminal amino-acid sequence that is the product of alternative splicing (isoform 2; Swiss-Prot P42701-3; sequences available at http://www.uniprot.org/uniprot/P42701; Fig. S3, A and B). To determine if human DCs splice the IL-12Rβ1 transcript after stimulation in a manner that is analogous to mouse DCs, we exposed monocyte-derived DCs to a variety of stimuli, some of which are
known inducers of DC IL-12Rβ1 expression (Nagayama et al., 2000). We then assessed the relative levels of transcripts for IL-12Rβ1 isoforms 1 and 2 using specific primers; cDNA from CD3+ PBMCs was used as a positive control. All samples expressed IL-12Rβ1 when assayed with primers that recognized both isoforms 1 and 2 (Fig. S3 C, top). However, amplification with primers specific to either isoform 1 (Fig. S3 C, middle) or isoform 2 (Fig. S3 C, bottom) revealed that these two transcripts were differentially expressed depending on the stimulus. Specifically, the production of isoform 2 was strongly associated with exposure to LPS, IL-1β, IL-2, and CCL3. Stimulation of human DCs with M. tuberculosis also elicited expression of IL-12Rβ1 isoform 2 over a 6-h time course (Fig. S3 D). We conclude from these experiments that human DCs, like mouse DCs, respond to specific stimuli by splicing the IL-12Rβ1 transcript.

Figure 6. IL-12Rβ1ΔTM is expressed in the M. tuberculosis-infected lung. C57BL/6 mice were aerogenically infected with 100 CFU M. tuberculosis. At the indicated times after infection the lungs of both (A) uninfected and (B) infected mice were harvested for IL-12Rβ1 spectratype analysis. Shown are representative spectra from (A) one individual uninfected mouse at each indicated time point or (B) two individual M. tuberculosis-infected mice from each time point. The numbers adjacent to peaks of an individual IL-12Rβ1 spectra indicate the relative ratio of that peak’s area (the smaller peak representing IL-12Rβ1ΔTM) to the area of the larger peak that represents IL-12Rβ1. (C) The ratio of IL-12Rβ1ΔTM to IL-12Rβ1 expressed in the lung of uninfected and M. tuberculosis-infected animals. (D) The ratio of IL-12Rβ1ΔTM to IL-12Rβ1 expressed in the liver of uninfected and M. tuberculosis-infected animals. Data points in C and D represent the mean and SD of the IL-12Rβ1ΔTM to IL-12Rβ1 ratios expressed in 4–8 individual mice per time point and are combined from two separate experiments; for the difference between infected lungs relative to uninfected lungs, *, P < 0.05; **, P < 0.005, as determined by Student’s t test.
(mRNAs) il12rb1 and il12rb1Δtm are expressed by CD11c+ cells in the M. tuberculosis–infected lung

We next asked whether (mRNA) il12b1Δtm is expressed in response to M. tuberculosis infection in vivo. To assess this, a time course of (mRNA) il12b1Δtm abundance relative to (mRNA) il12b1 in mice aerogenically infected with M. tuberculosis was performed. In uninfected controls, the expression of (mRNA) il12b1Δtm was minimal over the entire 30-d period, with (mRNA) il12b1 being the dominant transcript observed (Fig. 6 A). In M. tuberculosis–infected animals, however, a shift in the ratio of (mRNA) il12b1Δtm to (mRNA) il12b1 in the lung is observed at 9 d after infection (Fig. 6 B), with (mRNA) il12b1Δtm reaching 2.3-fold higher in abundance than (mRNA) il12b1 in some cases. After 9–12 d, the ratio of (mRNA) il12b1Δtm to (mRNA) il12b1 in the lung diminished, but still remained higher than that of uninfected controls up to day 30. This result was observed in several independent experiments (Fig. 6 C). In the liver, an organ distal to the initial site of infection, we observed elevated baseline levels of (mRNA) il12b1Δtm expression compared with the lung (Fig. 6 D); however, these levels remained unchanged through the early course of M. tuberculosis infection (Fig. 6 D). In summary, (mRNA) il12b1Δtm is expressed subsequent to M. tuberculosis infection in vivo—the relative ratio to (mRNA) il12b1 being dependent on time after infection.

The expression of IL-12Rβ1ΔTM by DCs in vitro (Fig. 5) and by the M. tuberculosis–infected lung in vivo (Fig. 6) prompted us to determine whether CD11c+ cells from M. tuberculosis–infected lungs are the source of this transcript. To do this, CD11c+ cells from the lungs of M. tuberculosis–infected mice were isolated by magnetic beads at various time points after infection and expression of (mRNA) il12b1Δtm was determined as described in Fig. 6. CD11c+ cells from M. tuberculosis–infected mice consistently expressed a higher ratio of (mRNA) il12b1Δtm to (mRNA) il12b1 compared with those isolated from uninfected controls, the highest being observed at 7–12 d after infection (compare top panels of Fig. 7, A and B). Notably, the CD11c− cells from M. tuberculosis–infected mice also expressed a higher ratio of (mRNA) il12b1Δtm to (mRNA) il12b1 compared with uninfected controls, the highest being observed at 20 and 30 d after infection (compare bottom panels of Fig. 7, A and B). This result was observed in several independent experiments (Fig. 7 C–D). These data demonstrate that after low-dose aerogenic M. tuberculosis infection, lung CD11c+ cells exhibit increased expression of (mRNA) il12b1Δtm and that CD11c− cells can also express this transcript as infection progresses.

Similar to M. tuberculosis, M. avium and Y. pestis are lung-tropic intracellular pathogens. Because exposure to M. avium, but not Y. pestis, increased DC expression of (mRNA) il12b1Δtm, we next determined if (mRNA) il12b1Δtm was also expressed in the M. avium– or Y. pestis–infected lung. For this, mice were aerogenically infected with M. avium (Fig. S4 A) or intranasally with Y. pestis KIMD27 (Fig. S4 C) and a time course of (mRNA) il12b1Δtm abundance relative to (mRNA) il12b1 was performed. As with M. tuberculosis, we observed a shift in the ratio of (mRNA) il12b1Δtm to (mRNA) il12b1 in the lung is observed at 9 d after infection (Fig. S4 B), with (mRNA) il12b1Δtm reaching 2.3-fold higher in abundance than (mRNA) il12b1 in some cases. After 9–12 d, the ratio of (mRNA) il12b1Δtm to (mRNA) il12b1 in the lung diminished, but still remained higher than that of uninfected controls up to day 30. This result was observed in several independent experiments (Fig. S4 C). In the liver, an organ distal to the initial site of infection, we observed elevated baseline levels of (mRNA) il12b1Δtm expression compared with the lung (Fig. S4 D); however, these levels remained unchanged through the early course of M. tuberculosis infection (Fig. S4 D). In summary, (mRNA) il12b1Δtm is expressed subsequent to M. tuberculosis infection in vivo—the relative ratio to (mRNA) il12b1 being dependent on time after infection.

The expression of IL-12Rβ1ΔTM by DCs in vitro (Fig. 5) and by the M. tuberculosis–infected lung in vivo (Fig. 6) prompted us to determine whether CD11c+ cells from M. tuberculosis–infected lungs are the source of this transcript. To do this, CD11c+ cells from the lungs of M. tuberculosis–infected mice were isolated by magnetic beads at various time points after infection and expression of (mRNA) il12b1Δtm was determined as described in Fig. 6. CD11c+ cells from M. tuberculosis–infected mice consistently expressed a higher ratio of (mRNA) il12b1Δtm to (mRNA) il12b1 compared with those isolated from uninfected controls, the highest being observed at 7–12 d after infection (compare top panels of Fig. 7, A and B). Notably, the CD11c− cells from M. tuberculosis–infected mice also expressed a higher ratio of (mRNA) il12b1Δtm to (mRNA) il12b1 compared with uninfected controls, the highest being observed at 20 and 30 d after infection (compare bottom panels of Fig. 7, A and B). This result was observed in several independent experiments (Fig. 7 C–D). These data demonstrate that after low-dose aerogenic M. tuberculosis infection, lung CD11c+ cells exhibit increased expression of (mRNA) il12b1Δtm and that CD11c− cells can also express this transcript as infection progresses.

Similar to M. tuberculosis, M. avium and Y. pestis are lung-tropic intracellular pathogens. Because exposure to M. avium, but not Y. pestis, increased DC expression of (mRNA) il12b1Δtm, we next determined if (mRNA) il12b1Δtm was also expressed in the M. avium– or Y. pestis–infected lung. For this, mice were aerogenically infected with M. avium (Fig. S4 A) or intranasally with Y. pestis KIMD27 (Fig. S4 C) and a time course of (mRNA) il12b1Δtm abundance relative to (mRNA) il12b1 was performed. As with M. tuberculosis, we observed a shift in the ratio of (mRNA) il12b1Δtm to (mRNA) il12b1 in the lung is observed at 9 d after infection (Fig. S4 B), with (mRNA) il12b1Δtm reaching 2.3-fold higher in abundance than (mRNA) il12b1 in some cases. After 9–12 d, the ratio of (mRNA) il12b1Δtm to (mRNA) il12b1 in the lung diminished, but still remained higher than that of uninfected controls up to day 30. This result was observed in several independent experiments (Fig. S4 C). In the liver, an organ distal to the initial site of infection, we observed elevated baseline levels of (mRNA) il12b1Δtm expression compared with the lung (Fig. S4 D); however, these levels remained unchanged through the early course of M. tuberculosis infection (Fig. S4 D). In summary, (mRNA) il12b1Δtm is expressed subsequent to M. tuberculosis infection in vivo—the relative ratio to (mRNA) il12b1 being dependent on time after infection.
in the lung at 8 d after infection with M. avium (Fig. S4 B). Despite similar numbers of CFU at 4 d after infection, only one out of five Y. pestis–infected animals showed expression of (mRNA) il12b1tm (Fig. S4 D, top). Negative results were also obtained upon infection with the more immunos- tumulatory strain Y. pestis KIMD27/pLpxL (Robinson et al., 2008; Fig. S4 D, bottom). Thus, although M. tuberculosis (Fig. 6) and M. avium induce expression of (mRNA) il12b1tm in the lungs, Y. pestis does not.

**IL-12Rβ1ΔTM enhances IL-12Rβ1-dependent migration**

DCs exhibit IL-12(p40)1– and il12b1–dependent migration in response to M. tuberculosis after only a 3-h exposure to this organism (Fig. 1 C; Khader et al., 2006; Robinson et al., 2008). Given that (mRNA) il12b1tm is generated and translated within this timeframe (Fig. 5), we investigated whether IL-12Rβ1ΔTM contributed to M. tuberculosis–induced, IL-12(p40)1–dependent DC migration. To do this, we selectively restored mRNAs that encode IL-12Rβ1, IL-12Rβ1ΔTM, or both IL-12Rβ1 and IL-12Rβ1ΔTM to il12b1tm–DCs, which contain a genomic neo insertion that disrupts exons 1–5 of the il12b1 locus (Wu et al., 1997) and thus lack both these proteins (Fig. 4). We co-transfected GFP encoding mRNA with the specific mRNAs via electroporation and found that an antibody specific for the common extracellular portion of the IL-12Rβ1 and IL-12Rβ1ΔTM only labeled GFP+ CD11c+ cells if mRNAs for either IL-12Rβ1 or IL-12Rβ1ΔTM were delivered to the il12b1tm–DCs (Fig. 8, A and B). After stimulation with *M. tuberculosis*, il12b1tm–DCs transfected with GFP and IL-12Rβ1 were capable of migrating toward CCL19 whereas those transfected with GFP alone were not (Fig. 8 C). il12b1tm–DCs transfected with GFP and IL-12Rβ1ΔTM had migratory levels equivalent to those transfected with GFP alone. However, cotransfection with GFP, IL-12Rβ1 and IL-12Rβ1ΔTM resulted in a greater chemotaxis index than when DCs were transfected with GFP and IL-12Rβ1. The majority of migrated cells were GFP+, suggesting that migration required transfection of the migrating cell and was not an indirect effect (Fig. 8 D). These data demonstrate that IL-12Rβ1ΔTM can enhance IL-12Rβ1–dependent DC migration.

Finally, given that IL-12Rβ1ΔTM enhanced IL-12Rβ1–dependent DC migration in vitro, we determined whether its expression in DCs accelerated the activation of *M. tuberculosis*–specific T cells in vivo. il12b1tm–BMDCs were selectively restored with mRNAs for IL-12Rβ1, IL-12Rβ1ΔTM, or both IL-12Rβ1 and IL-12Rβ1ΔTM as described in Fig. 8. After their electroporation and overnight culture, DCs were cultured with irradiated *M. tuberculosis* and ESAT1–10 peptide for 3 h. After this period, DCs were washed and instilled via the trachea into the lungs of C57BL/6 mice that had previously received 5 × 10^5 CFSE-labeled ESAT-TCR CD4+ cells. 12 h after DC instillation, the surface expression of CD44 and CD69 by CFSE+CD4+ cells in the draining MLN was assessed by flow cytometry. As anticipated, mice that received sham electroporated il12b1tm–DCs had fewer activated *M. tuberculosis*–specific T cells in the draining MLN relative to those that received sham electroporated C57BL/6 DCs (Fig. 8 E). Restoration of IL-12Rβ1 alone to il12b1tm–DCs elevated the frequency of CD44+ and CD62L+ *M. tuberculosis*–specific T cells; however, restoring IL-12Rβ1ΔTM alone to il12b1tm–DCs did not elevate the frequency of activated M. tuberculosis–specific T cells. Importantly, only when both IL-12Rβ1 and IL-12Rβ1ΔTM were restored to il12b1tm–DCs did the frequency of activated *M. tuberculosis*–specific T cells return to the level seen in mice that received C57BL/6 DCs. This result was observed across several independent experiments (Fig. 8, F and G). These data demonstrate that IL-12Rβ1ΔTM can enhance IL-12Rβ1–dependent migration from the lung and activation of *M. tuberculosis*–specific T cells in the lung draining MLN.

**DISCUSSION**

DCs are pivotal for initiating immunity to *M. tuberculosis* and other diseases of the pulmonary tract (Tian et al., 2005; Lambrecht, 2008), and they have been shown to transport *M. tuberculosis* from the lungs to the MLN (Wolff et al., 2007). IL-12 family members are secreted by DCs after Mtb stimulation (Jang et al., 2008) and are required for their ability to generate an efficient T cell response (Zhang et al., 2003; Khader et al., 2006). Here, we demonstrate that after their encounter with *M. tuberculosis*, DCs express IL-12Rβ1 and an IL-12Rβ1 splice variant that we have termed “IL-12Rβ1ΔTM.” In contrast to IL-12Rβ1, IL-12Rβ1ΔTM contains an altered C-terminal sequence and lacks a transmembrane domain; nevertheless, IL-12Rβ1ΔTM is still membrane associated. Selective reconstitution of il12b1tm–DCs with IL-12Rβ1 and/or IL-12Rβ1ΔTM demonstrates that IL-12Rβ1ΔTM augments IL-12Rβ1–dependent DC migration; however, it cannot substitute for IL-12Rβ1. Importantly, after *M. tuberculosis* infection of the lung, CD11c+ cells in this organ express IL-12Rβ1ΔTM. Further, reconstitution of il12b1tm–DCs with IL-12Rβ1 and IL-12Rβ1ΔTM accelerates in vivo CD4+ T cell activation compared with il12b1tm–DCs reconstituted with IL-12Rβ1 alone. Thus, we propose that in response to *M. tuberculosis* DCs express IL-12Rβ1ΔTM, a novel positive regulator of IL-12Rβ1–dependent signaling, and that this enhances IL-12Rβ1–dependent migration and *M. tuberculosis*–specific CD4+ T cell activation.

Alternative splicing is emerging as an important regulator of immunity (Lynch, 2004). It is estimated that >75% of human genes undergo alternative splicing, many of which are exclusively expressed by the immune system (Johnson et al., 2003). The list of proteins regulated by splicing includes those involved in intracellular signaling cascades (i.e., Fyn and Syk), membrane adhesion (i.e., CD31, CD44, and CD54), and cell activation (i.e., CD45 and CD152; Lynch, 2004). Alternatively spliced cytokine receptors can regulate inflammatory events by functioning as either agonists or antagonists of cytokine signaling (Levine, 2004). The list of alternatively
Figure 8. IL-12Rβ1ΔTM enhances IL-12Rβ1-dependent migration. (A–D) il12rb1−/− CD11c+ BMDCs were transfected with mRNAs encoding either GFP, GFP and IL-12Rβ1, GFP and IL-12Rβ1ΔTM, or GFP and IL-12Rβ1 and IL-12Rβ1ΔTM. 24 h later, (A) cells were analyzed by flow cytometry for GFP expression among CD11c+ cells and (B) expression of transfected IL-12Rβ1 was examined by gating on GFP+CD11c+ cells. (C) The migratory ability of DCs transfected with the indicated mRNAs was assessed as performed in Fig. 1 C. Data points represent the mean and SD of the combined data from three separate experiments with different BM preparations per experiment. For the difference between CI induced in the indicated groups, *, P < 0.05, as determined by Student’s t test. (D) Flow cytometric analysis of those cells that had migrated and transfected with GFP and IL-12Rβ1 and IL-12Rβ1ΔTM demonstrates that the migratory DCs from this group were mostly GFP+. (E) We compared the ability of il12rb1−/− DCs transfected with indicated mRNAs to activate M. tuberculosis-specific T cells in vivo; sham-transfected C57BL/6 DCs were used as a positive control. After transfection the indicated DCs
spliced cytokine receptors include members of the class I cytokine receptor superfamily (IL-4R, IL-5R, IL-6R, IL-7R, IL-9R, EpoR, GCSF R, GMCSFR, gp130, and LIFR), class II cytokine receptor superfamily (IFNAR1 and IFNAR2), IL-1/TLR family (IL-1RI and IL-1RacP), TGF receptor family (TIR and activin receptor-like kinase 7), and TNFR superfamily (TNFRSF6/Fas/CD95, TNFRSF9/4-1BB/CD137, and IL-17R; Levine, 2004).

To this list of spliced and functioning cytokine receptors we can now add IL-12R1TM. The mouse IL-12R1 and IL-12R1TM cDNAs were originally cloned based on their nucleotide homology to human IL-12R1 (Chua et al., 1995). When transfected into COS cells, both cDNAs produced proteins that bind [125I]IL-12 with similar low affinities, suggesting that IL-12R1 and IL-12R1TM were both expressed on the cell surface (Chua et al., 1995). However, no function had or has been ascribed to IL-12R1TM since that time. Here, we have demonstrated that although mouse IL-12R1TM cannot substitute for IL-12R1, it can function in DCs to enhance IL-12(p40)+ and IL-12R1-dependent migration. That this may be relevant to our understanding of human DC biology is suggested by our observation that human PBMC-derived DCs also respond to stimulation by splicing (mRNA) IL12RB1 to generate a protein with similar characteristics as the mouse variant. Curiously, for humans, the stimuli that elicit (mRNA) IL12RB1 splicing are broader in origin than for mice. Whether human IL-12R1TM expression performs the same function in nonhuman DCs should certainly be investigated. It should be mentioned that IL-12R1TM expression is likely not restricted to DCs and may augment functions other than migration. The expression of (mRNA) il12b1 and (mRNA) il12b1tm in the CD11cneg fraction of M. tuberculosis-infected lungs suggests that the proteins encoded by these sequences may play a role during the chronic stage of infection. Whether IL-12R1TM functions to enhance IL-12R1-dependent processes in T and NK cells is a focus of future investigations.

Further questions raised by the data include which signaling pathways are required in order for (mRNA) IL-12R1 to be spliced? Our data demonstrate that for mouse DCs, both M. tuberculosis and M. avium elicit (mRNA) IL-12R1 splicing, whereas Y. pestis stimulation does not; this despite the fact that Y. pestis does induce DC migration (Robinson et al., 2008). This suggests that although induction of (mRNA) il12b1 is sufficient for DC migration, the augmented migration resulting from induction of (mRNA) il12b1tm is a unique aspect of mycobacterial activation of DCs. We have begun to address the molecular mechanism by which IL-12R1TM augments DC migration and show that IL-12R1–deficient DCs have a reduced M. tuberculosis–dependent NF-κB activation and that IL-12(p40)2 can induce NF-κB activation alone and augment M. tuberculosis–dependent NF-κB activation. Because it lacks any known intracellular signaling capacity, IL-12R1TM may enhance IL-12R1–mediated NF-κB activation by increasing the affinity of IL-12(p40)2 for IL-12R1 or by forming some other structure that favors IL-12(p40)+ signaling. In particular, as IL-12p40 binds only to dimer/oligomers of IL-12R1 (Chua et al., 1995), it is possible that the IL-12R1TM stabilizes oligomerization of IL-12R1. Although it is possible that the splice variant may be sequestered into the supernatant, we have not been able to detect it in this fraction, even after 10-fold concentration, which leads us to postulate that the splice variant acts at the membrane. Future investigations in our laboratory will test this idea, as well as determine how IL-12R1TM remains membrane-associated despite the absence of a TM-domain.

A large body of data demonstrates the essential function that the IL12RB1 gene serves in humans to positively regulate immunity to mycobacterial pathogens. The association between IL12RB1 deficiency and mycobacterial susceptibility undoubtedly reflects the importance of the IL12RB1 gene to a wide variety of cell types. The expression of human IL12RB1 mRNA is increased during active pulmonary tuberculosis in humans (Taha et al., 1999); expression of human IL12R1TM during pulmonary tuberculosis has never been assessed. Although this study has focused on the importance of il12b1 to DC function after their exposure to M. tuberculosis, our data present a novel pathway whereby a deficiency in IL-12R1TM results in an impaired DC function and reduced T cell activation. The generation of a mouse specifically lacking IL-12R1TM but not IL-12R1 is underway, and this will further our understanding of this important pathway.

MATERIALS AND METHODS

Mice. All mice were bred at the Trudeau Institute and were treated according to National Institutes of Health and Trudeau Institute Animal Care and Use Committee guidelines. All animal protocols were approved by the Trudeau Institute Animal Care and Use Committee. C57BL/6, B6.129S1-Il12rb1tm1jm/J (i.e., il12b1+/− mice; Magram et al., 1996), B6.129S1-B12h2tm1/j (i.e., il12b1−/− mice; Wu et al., 2000), and B6.FVB-Tg(Itgax-DTR/Egfp)57Lan/J (i.e., CD11c-DTR; Jung et al., 2002) mice were originally purchased from The Jackson Laboratory. C57BL/6 mice deficient of the B6.129S1-B12h2tm1/j (il12b1−/−) mice have been previously described (Wu et al., 1997), as have ESAT61-20–specific TCR-transgenic mice (Reiley et al., 2008).

Cell preparations. M. tuberculosis infections were performed and the lung tissue and lymph nodes were processed as described previously (Khader et al., 2007). Single-cell suspensions were prepared from either digested lung populations were cultured with M. tuberculosis and ESAT61-20 peptide; after this they were instilled via the trachea into C57BL/6 mice containing transferred CFSE-labeled ESAT-specific CD4+ cells. Shown are histograms of CD44 and CD69 expression on CFSE+CD4+ 12 h later in the draining MLN. Each histogram is representative of four mice per condition. (F and G) The combined (F) CD44 and (G) CD69 data gated on CFSE+CD4+ in the draining MLN are shown; these data are representative of two independent experiments with three to four mice per group.
tissue or lymph nodes by direct dispersal through a 70-µm nylon tissue strainer (BD). The resultant suspension was treated with Gey’s solution (155 mM NaCl, 10 mM KHCO3) to remove any residual red blood cells, washed twice with complete media, counted, and stained for subsequent flow cytometric analysis.

**BMDCs.** BMDCs were generated from BM of 4–5-wk-old C57BL/6 mice harvested via perfusion of the femur and tibia medullary cavities with ice cold DMEM. Marrow suspensions were pelleted and incubated in Gey’s solution to lyse red blood cells, and the marrow was then resuspended at 4 × 105 cells/ml in complete supplemented DMEM (cDMEM). 5 ml of BM homogenate was plated in a Petri dish (Corning, Inc.) along with 5 ml of 40 ng/ml recombinant murine GM-CSF (PeproTech) in cDMEM solution for a final concentration of 20 ng/ml GM-CSF. Cultures were maintained at 37°C at 5% CO2 for 3 d, at which time an additional 10 ml of 20 ng/ml GM-CSF in cDMEM was added. At 6 d, nonadherent cells were collected and the presence of CD11c+ cells confirmed by flow cytometric analysis. For indicated experiments CD11c+ cells were positively selected by magnetic purification. In these cases 106 CD11c+ cells were placed in a 2 ml homogenate was pelleted (270 × g) and resuspended in 2 ml of PBS, 0.1% BSA, 0.1% sodium azide. For the generation of Concanavalin A blasts, C57BL/6 spleens were dispersed through a 70-µm nylon cell strainer (BD) and the cellular homogenate was pelleted (270 g, 6 min at 4°C) and resuspended in 2 ml of Gey’s solution to remove red blood cells. Splenocytes were washed and resuspended at 20 × 106 cells/ml in cDMEM, and 1 ml of splenocytes was plated in 6-well dishes (Corning, Inc.) along with 1 ml of 10 µg/ml Concanavalin A in cDMEM solution (Sigma-Aldrich) for a final concentration of 5 µg/ml Concanavalin A. Cultures were maintained at 37°C at 5% CO2 for 3 d before cells were harvested for RNA and/or protein as indicated.

**RNA purification and cDNA synthesis.** Total RNA was isolated from indicated tissues and/or cell populations using the RNeasy method (Qiagen) and was treated with DNase (Ambion). cDNA was subsequently synthesized using SuperScript II reverse transcription PCR kit (Invitrogen) with random hexamer primers.

**PCR.** To amplify the IL-12Rβ1 transcript, we used primer pairs that selectively amplify the extracellular, transmembrane, or intracellular encoding portions. The relative positions of these primers (labeled P1-P6) are illustrated in Fig. 3 B. P1–4 sequences are taken directly from a previous study of IL-12Rβ1 expression in DCs (Grohmann et al., 1998). The 5′–3′ sequences of these and the other primers used in our study are as follows: P1, 5′-ATGACGAGCTCTGCGAGTAT-3′; P2, 5′-GCTGATGGCTCAAT-3′; P3, 5′-AATTGTCCTGCGCCAAACTCG-3′; P4, 5′-GCCAATGTATGGAGACTGC-3′. Primer P5 was designed for this study; its sequence is as follows: 5′-CCGTCCTGGCTCCTGGACT-3′. IL-12Rβ1 transcripts were amplified by PCR in a 25-µl reaction comprising the following: 2.5 µl of a 10× PCR buffer (200 mM Tris, pH 8.4, 500 mM KC), 0.5 µl of 10 mM dNTPs, 1 µl 50 mM MgCl2, 0.1 µl of 5 µM forward primer (P1 or P3), 1 µl of 5 µM reverse primer (P2, P4 or P5), 17.9 µl of DNase-free H2O, and 1 µl of cDNA (a minimum of 200 pg cDNA). After denaturation at 94°C for 3 min, the reaction was cycled forty times under the following conditions: 94°C for 45 s, 60°C for 30 s, and 72°C for 90 s. The products of this reaction were analyzed on a 2% agarose gel or kept for IL-12Rβ1 spectratype analysis as described in the following section.

**IL-12Rβ1 spectratype analysis.** IL-12Rβ1 spectratype analysis of IL-12Rβ1 and IL-12Rβ1ΔTM mRNAs, and the quantification of the resultant data, was a modification of the now commonly used TCR-CD3 spectratype analysis (Pannetier et al., 1993). IL-12Rβ1 and IL-12Rβ1ΔTM cDNA transcripts were first amplified by PCR in the 25-µl reaction detailed above with the forward primer 5′-CAGCCGAGTAAATGTACAAGG-3′ and reverse primer 5′-CTGCTCCTGGCTCCTGGACT-3′. The forward primer corresponds to nt 1653–1672 of the mouse IL-12Rβ1 sequence (GenBank accession no. NM_008941). The reverse primer resides upstream of the transmembrane-encoding sequence (nt 1739–1834). The IL-12Rβ1 transcript was amplified by PCR in a 25-µl reaction comprising the following: 2.5 µl of a 10× PCR buffer (200 mM Tris, pH 8.4, 500 mM KC), 0.5 µl of 10 mM dNTPs, 1 µl 50 mM MgCl2, 0.1 µl of 5 µM forward primer (P1 or P3), 1 µl of 5 µM reverse primer (P2, P4 or P5), 17.9 µl of DNase-free H2O, and 1 µl of cDNA (a minimum of 200 pg cDNA). After denaturation at 94°C for 3 min, the reaction was cycled forty times under the following conditions: 94°C for 45 s, 60°C for 30 s, and 72°C for 90 s. The products of this reaction were analyzed on a 2% agarose gel or kept for IL-12Rβ1 spectratype analysis as described in the following section.

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**Plasmids and transfections.** Plasmids expressing IL-12Rβ1 and IL-12Rβ1ΔTM cDNAs in vector pEF-BOS (Mizushima and Nagata, 1990) under the EF1α promoter have been described (Chua et al., 1995;...
pEF-BOS.IL-12Rβ1 and pEF-BOS.IL-12Rβ1ΔTM). pAcGFP1-N1 (Takara Bio Inc.) was used to express eGFP under the CMV promoter to identify transfected cells. For transfection into NIH/3T3 cells (American Type Culture Collection) we used the Polyfect system (QIAGEN) after the manufacturers instructions.

**Western blot analysis.** SDS-PAGE analysis of reduced protein samples and Western blot analysis. Type Culture Collection) was run simultaneously with each gel.

**NF-κB EMSA.** Nuclear extracts from indicated cell populations were subjected to polyacrylamide electrophoresis and EMSA analysis of subsequently generated blots with a NF-κB EMSA kit (Panomics) with biotinylated NF-κB probe 5′-AGTTGAGGGGACTTTCCAGGC-3′, as per the manufacturer’s instructions.

**In vitro mRNA transcription.** To generate in vitro–transcribed (IVT) mRNA of IL-12Rβ1, IL-12Rβ1ΔTM and eGFP it was first necessary to subclone their respective cDNAs into a second plasmid, downstream of a T7 phage polymerase. The IL-12Rβ1 and IL-12Rβ1ΔTM cDNAs were first amplified out of their pEF-BOS backbones using primers that flanked their start and stop codons; specifically 5′-GGTTCCTGACCGGATCAGAC-3′ and 5′-CCGAGCTCTTATGGGTCCT-3′. eGFP was amplified out of pAcGFP1-N1 using primers 5′-TAGCGCTACCGGACTCAGAT-3′ and 5′-GCCAACTTGGGACACCTTGAT-3′. The conditions used to amplify with these primers were the same as those used for the primary PCR of IL-12Rβ1 spectratype analysis detailed above. cDNA from CD3+ PBMCs amplified with these primers were the same as those used for the primary PCR of IL-12Rβ1 isoforms 1 and 2 (Common: forward, 5′-ACACTCTGTTGGAATACTCTGCT-3; reverse, 5′-GCCAACCTTGACACCTTGAT-3), only isoform 1 (Specific 1: forward, 5′-ACACTCTGGTGAATCCTGCT-3; reverse, 5′-CCACCTTCTCTGACCTCAAC-3) or isoform 2 (Specific 2: forward, 5′-ACACTCTGGTGAATCCTGCT-3; reverse, 5′-CACCCTTGAGGCAACG-3). The conditions used to amplify with these primers were the same as those used for the primary PCR of IL-12Rβ1 isoforms 1 and 2 (Common: forward, 5′-ACACTCTGTTGGAATACTCTGCT-3; reverse, 5′-CCACCTTCTCTGACCTCAAC-3).

**Statistical analysis.** Differences between the means of experimental groups were analyzed with the two-tailed Student’s t test as the data were considered parametric. Differences with a P value of 0.05 or less were considered significant. Prism software was used for all analyses.

**Online supplemental material.** Fig. S1 demonstrates the concept and validation of IL-12Rβ1 spectratype analysis. Fig. S2 shows that the expression of IL-12Rβ1ΔTM mRNA by mouse DCs is limited to mycobacterial stimulation. Fig. S3 demonstrates that two isoforms of IL-12Rβ1 are expressed by human DCs after exposure to M. tuberculosis and other specific stimuli. Fig. S4 shows that lung expression of IL-12Rβ1ΔTM mRNA also occurs during pulmonary infection with M. avium, but not Y. pestis. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.200910855/D1C1.

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**In vivo migration of electroporated DCs.** After mRNA electroporation and overnight culture, 106 DCs were cultured with 10 µg/ml irradiated M. tuberculosis and 1 µM ESAT6,30 peptide for 3 h. After this time the DCs were washed, resuspended in PBS, and instilled via the trachea into the lungs of C57BL/6 mice. 18 h before instillation, each mouse had intravenously received 5 × 106 CFSE-labeled ESAT-TCR CD4+ cells. The surface expression of CD44 and CD69 on CFSE+CD4+ cells in the draining MLNs was assessed 12 h later by flow cytometry.

**IL-12Rβ1 isoform expression by human DCs.** Monocyte-derived DCs were generated by incubating magnetically puriﬁed CD14+ monocytes from apheresis samples for 7 d with 20 ng/ml GMSCF (Peprotech) and 50 ng/ml IL-4 (R&D Systems). DCs were then incubated for 24h with 1 µg/ml LPS or for 3 d with either of the following: 10 ng/ml IL-1β, 200 ng/ml IL-10, 10 ng/ml IL-6, 20 U/ml IL-2, 50 ng/ml CCL3, 50 ng/ml PIGF, or just RPMI media (control). Alternatively, DCs were stimulated with M. tuberculosis over a 6-h period. Subsequently generated cDNA from these populations was then ampliﬁed with primer pairs that either ampliﬁed both IL-12Rβ1 isoforms 1 and 2 (Common: forward, 5′-ACACTCTGGTGAATACTGCT-3; reverse, 5′-GCCAACCTTGACACCTTGAT-3), only isoform 1 (Specific 1: forward, 5′-ACACTCTGGTGAATCCTGCT-3; reverse, 5′-CCACCTTCTCTGACCTCAAC-3) or isoform 2 (Specific 2: forward, 5′-ACACTCTGGTGAATCCTGCT-3; reverse, 5′-CACCCTTGAGGCAACG-3). The conditions used to amplify with these primers were the same as those used for the primary PCR of IL-12Rβ1 isoforms 1 and 2.

**Electroporation of DCs.** Electroporation of individual mRNAs into IL12B1ΔTM DCs was done as performed by Ponsaerts et al. (2002), with minor modiﬁcations. In brief, before electroporation, DCs were washed twice with electroporation buffer (Ambion) and resuspended to a ﬁnal concentration of 5 × 106 cells/ml in electroporation buffer. Subsequently, 0.2 ml of the cell suspension was mixed with 20 µg of IVT mRNA and electroporated in a 0.4-cm cuvette at 300 V and 150 µF using a Gene Pulser Xcell Electroporation System (Bio-Rad Laboratories). After electroporation, fresh complete medium was added to the cell suspension and cells further incubated at 37°C in a humidified atmosphere supplemented with 5% CO2. For all electroporation experiments, the co-transfection of eGFP-mRNA was used to both conﬁrm transfection eﬃciency and to identify those cells that have been successfully transfected.
Splicing of il12rb1 alters DC migration | Robinson et al.


