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Lymphotoxin β Receptor Activation on Macrophages Induces Cross-Tolerance to TLR4 and TLR9 Ligands

Nadin Wimmer,* Barbara Huber,* Nicola Barabas,* Johann Röhr,* Klaus Pfeffer,† and Thomas Hehlgans*

Our previous studies indicated that lymphotoxin β receptor (LTβR) activation controls and downregulates inflammatory reactions. In this study, we report that LTβR activation on primary mouse macrophages results in induction of tripartite motif containing (TRIM) 30α, which negatively regulates NF-κB activation induced by TLR signaling. LTβR activation results in a downregulation of proinflammatory cytokine and mediator expression upon TLR restimulation, demonstrating that LTβR signaling is involved in the induction of TLR cross-tolerance. Specific knockdown experiments using TRIM30α-specific small interfering RNA abolished the LTβR-dependent induction of TRIM30α and LTβR-mediated TLR cross-tolerance. Concordantly, LTβR activation on bone marrow-derived macrophages induced cross-tolerance to TLR4 and TLR9 ligands in vitro. Furthermore, we have generated cell type-specific LTβR-deficient mice with ablation of LTβR expression on macrophages/neutrophils (LTβR<sup>fl<sup>ox<sup>/fl<sup>ox</sup> × LysM-Cre<sup>+</sup>)). In bone marrow-derived macrophages derived from these mice LTβR-induced cross-tolerance to TLR4 and TLR9 ligands was impaired. Additionally, mice with a conditional ablation of LTβR expression on macrophages (LTβR<sup>fl<sup>ox<sup>/fl<sup>ox</sup> × LysM-Cre<sup>+</sup>)) are resistant to LTβR-induced TLR4 tolerance in vivo. Collectively, our data indicate that LTβR activation on macrophages by T cell-derived lymphotoxin α<sub>1</sub>β<sub>2</sub> controls proinflammatory responses by activation of a TRIM30α-controlled, counterregulatory signaling pathway to protect against exacerbating inflammatory reactions. *The Journal of Immunology, 2012, 188: 000–000.

Inflammation is a complex pathophysiological condition initially mediated primarily by innate immune cells in response to infection and/or tissue damage (1, 2). Innate immune cells detect and respond to danger signals such as pathogens and/or tissue damage by activating their TLRs on their cell surface. However, chronic and repeated stimulation through TLRs renders immune cells hyporesponsive to subsequent stimulation, a phenomenon known as TLR tolerance (3). The activation of innate immune cells triggers a robust but essential inflammatory response that needs to be tightly regulated (4, 5). Uncontrolled inflammatory reactions lead to extensive tissue damage and the manifestation of pathophysioplogical conditions such as chronic inflammation, sepsis, and autoimmune disease (6). Membrane-anchored lymphotoxin (LT)α<sub>1</sub>β<sub>2</sub> and LIGHT, both members of the TNF superfamily, are functional ligands for the LTβ receptor (LTβR). Both ligands are expressed only on activated lymphocytes, NK cells, and a subset of follicular B cells, whereas the LTβR is primarily expressed on epithelial and stromal cells and cells of the myeloid lineage (7, 8). So far, most studies have focused on the critical role of LTβR signaling in the development and maintenance of secondary lymphoid organ integrity (9–11) and the control of dendritic cell-mediated immune homeostasis (12, 13). Furthermore, some reports have demonstrated a critical role for LTβR signaling for the protection against Citrobacter rodentium-induced colitis (14, 15) and Mycobacterium tuberculosis, Listeria monocytogenes (16), as well as cytomegalovirus (17) infections. Recent results have shown that ablation of LTβR signaling using either a functional inhibitor of LTβR activation (LTβR: Ig) or LTβR-deficient mice or mice deficient for the T cell-derived ligand LTβR results in a significant aggravation of inflammation (18). Activation of the LTβR by its membrane-associated ligand LTαβ, but not LIGHT, seems to be crucial for the downregulation of the inflammatory response (19). However, the cellular and molecular mechanisms underlying this protective role of LTβR activation have so far not been elucidated.

In this study we have identified tripartite motif containing (TRIM) 30α, a negative regulator of TLR-induced NF-κB activation, as a target gene of LTβR signaling in bone marrow-derived macrophages (BMDM). LTβR-induced TRIM30α expression inhibits the production of proinflammatory cytokines and mediators upon TLR4 and TLR9 restimulation, demonstrating, to our knowledge, for the first time that LTβR activation induces cross-tolerance in TLR-induced cytokine and proinflammatory mediator production.

Furthermore, we have generated cell type-specific LTβR-deficient mice with ablation of LTβR expression on macrophages/neutrophils (LTβR<sup>fl<sup>ox<sup>/fl<sup>ox</sup> × LysM-Cre<sup>+</sup>)). BMDM derived from these mice are resistant to TLR4 and TLR9 tolerance in vitro. Additionally, no tolerance could be induced in the model of TLR4-induced cytokine production in vivo. Collectively, our data suggest that cell-type specific LTβR signaling is critically involved in the regulation of innate inflammatory immune reactions.
Materials and Methods

Generation of LTβR floxed mice

A genomic clone derived from a mouse 129svJ genomic library encompassing the complete coding sequence for the LTβR locus has been described earlier (9). This clone was modified by introducing an FRT-flanked neomycin resistance cassette following by a loxP signal at the 3′ end into the EcoRV restriction site within the 5′ untranslated region of the LTβR gene. Additionally, a second loxP site had been introduced into the second intron of the LTβR gene.

E14.1 embryonic stem (ES) cells were transfected with linearized LTβR targeting vector as described (20). G418-resistant ES cell colonies were picked. Homologous recombination was screened by PCR and subsequently confirmed by genomic Southern blotting after digest of the ES cell DNA with EcoRI and hybridization of the flanking probe, located 5′ of the targeting vector in the genomic locus. Location and orientation of both loxP sites and the FRT flanked neomycin resistance cassette were verified by cloning of the corresponding PCR products and subsequent sequence analysis. Single integration of the targeting vector was verified by Southern probing with the neomycin resistance cassette. Chimeric mice were generated as described (20). Deletion of the neomycin resistance cassette in vivo was achieved by breeding chimeric mice with FLPe deleter mice (21). Deletion of the neomycin resistance cassette was verified by Southern blotting. Mice were housed in an animal facility with barrier conditions. For genotyping by PCR the following primers were used: 5′-GAAGATACAGAGAATCGGACG-3′ and 5′-CTATAGGACATGGGAAAGAGGG-3′.

Mice

Female C57Bl/6 mice (wild-type) were obtained from Janvier (Le Genest, France). LTβR-deficient mice (LTβR−/−), LTBβ-deficient mice (Ltbβ−/−), and LIGHT-deficient mice (LIGHT−/−) have been described previously (9, 22–25). MyD88-deficient mice (MyD88−/−) and TNF-deficient mice (TNF−/−) were housed at the animal facility of the University of Regensburg and have been described previously (26, 27). Mice used for experiments were age, sex, and weight matched.

In vitro stimulation assays

The mouse macrophage cell line J774 (ATCC TIB-67) was maintained in humidified 5% CO2 at 37°C in RPMI 1640 supplemented with 10% heat-inactivated FCS, 100 U/ml penicillin, and 100 U/ml streptomycin. BMDM were generated as described previously (28). Stimulations were performed at day 7 in triplicates (1 × 106 cells/ml) using 10 μg/ml agonistic anti-LTβR mAb (clone 5G11b, IgG2a; Hycult Biotech, Uden, The Netherlands), 10 μg/ml rat IgG (Sigma-Aldrich, Taufkirchen, Germany), or 100 ng/ml LPS from Salmonella enterica serotype abortus equi (Sigma-Aldrich, Hamburg, Germany) for the indicated times. Naive CD4+ T cells were purified from single-cell suspensions of spleen using a CD4+ T cell isolation kit II (Miltenyi Biotec, Bergisch-Gladbach, Germany). Reanalysis demonstrated a purity of >94% (data not shown). CD4+ T cells were stimulated with PMA (50 ng/ml) and ionomycin (500 ng/ml) (Sigma-Aldrich) for 14 h, additionally treated for 4 h with 10 μg/ml mLTβR-Ig or left unstimulated. T cells were washed three times with RPMI 1640 and cocultured in increasing ratios (1:1, 1:5, and 1:10) with BMDM for 24 h in RPMI 1640 (Sigma-Aldrich) supplemented with 10% inactivated FCS, 100 U/ml penicillin, and 100 U/ml streptomycin.

Flow cytometry

Expression of LTβR was detected by FACS analysis (BD LSR II; BD Biosciences, San Jose, CA) using a specific rat anti-mLTβR biotin-conjugated Ab (clone 3C8, IgG1; eBioscience, San Diego, CA) or an irrelevant isotype-matched rat IgG as negative control followed by an allophycocyanin-conjugated streptavidin Ab.

Small interfering RNA experiments

J774 cells were transiently transfected with 1 nM TRIM30α-specific small interfering (siRNA) or scrambled siRNA using INTERFERN® siRNA transfection reagent (Polyplus-Transfection, Illkirch, France) according to the manufacturer’s instructions. The siRNA constructs were designed as described (29). TLR tolerance

The cells were not stimulated or were preincubated with 10 μg/ml rat IgG, 10 μg/ml agonistic anti-mLTβR mAb, or 100 ng/ml LPS (S. enterica serotype abortus equi; Sigma-Aldrich) for 30 h, washed twice with medium, and rechallenged with 100 ng/ml LPS or 1 μM CpG (Metabion, Martinsried, Germany) for 8 h or 200 ng/ml LPS and 20 ng/ml mouse IFN-γ (AbD Serotec, Kidlington, U.K.) for 24 h. TNF and IL-6 were measured in the supernatants by ELISA. Nitrite accumulation in the cell culture supernatants was measured by using the Griess assay.

On days 5 and 3 mice were i.p. pretreated with PBS, LPS (Escherichia coli, 0127:B8; Sigma-Aldrich) (50 μg/kg or 20 μg/kg), rat IgG (100 μg/mouse), or agonistic anti-mLTβR mAb (100 μg/mouse). On day 0 the mice were challenged with LPS at a dose of 10 μg/mouse. Serum was collected 1 h later and TNF was measured by ELISA. For analysis of the TRIM30α expression in vivo, mice were killed on day −2, resident peritoneal exudate cells (RPEC) were obtained by lavage of the peritoneum with 10 ml ice-cold RPMI 1640 containing 10% FCS.

RNA isolation and quantitative RT-PCR

Total RNA from cultured cells was extracted by using the NucleoSpin RNA II kit (Macherey-Nagel, Duren, Germany) following the manufacturer’s instructions. RNA was transcribed using the Promega (Mannheim, Germany) reverse transcription system following the manufacturer’s recommendations. Quantification of mouse TRIM30α mRNA was performed using an iQ multicolor real-time PCR detection system (Bio-Rad, München, Germany) following the manufacturer’s recommendations. For standardization, β2AS RNA was amplified. Primers specific for TRIM30α were purchased from SABiosciences (Frederick, MD) following the manufacturer’s recommendations.

Western blotting

Analysis of TRIM30α protein expression was done using a polyclonal rabbit anti-TRIM30α antiserum generated by immunization of keyhole limpet hemocyanin-conjugated TRIM30α peptide (LHSSIQKQNVLFQ) synthesized by BioGenes (Berlin, Germany), as well as peroxidase-conjugated goat anti-rabbit IgG (whole molecule) Ab (Sigma-Aldrich). The detection of β-actin was performed with a peroxidase-conjugated chicken anti-mouse β-actin (Santa Cruz Biotechnology, Santa Cruz, CA).

ELISA

Mouse TNF, IL-6, and IFN-γ levels were measured with ELISA kits (R&D DuoSets; R&D Systems, Wiesbaden, Germany) according to the manufacturer’s protocol.

NO production

The NO production was determined using a Griess assay as described previously (30). The samples were analyzed in triplicates.

Statistics

Statistical analysis was performed using the Student t test. Data are expressed as mean ± SD, and p < 0.05 was considered statistically significant.

Results

Generation of cell type-specific LTβR-deficient mice

To study the cellular and molecular mechanisms underlying the protective role of LTβR activation against an exacerbated inflammatory reaction, we generated macrophage/neutrophil-specific LTβR-deficient mice by crossing LTβRfloxed mice with LysM-Cre mice (Fig. 1). To inactivate the LTβR cell type specifically we made use of both the Cre/loxP and FRT/FLP technology (21, 31). In the LTβR targeting vector encompassing the entire genomic LTβR gene locus, a 5′ loxP site was inserted into the second intron of the LTβR gene (Supplemental Fig. 1). Additionally, a neomycin marker cassette flanked by FRT sites and a 3′ loxP site were inserted into the 3′ untranslated region of the LTβR gene. The targeting vector was introduced into mouse ES cells and homologous recombination was verified by Southern blot and PCR analysis (Fig. 1A, 1B). After germline transmission, heterozygous LTβRfl/+ mice were crossed with FLPe deleter mice to delete the neomycin cassette in vivo. Deletion was verified by Southern blot analysis using a neomycin-specific probe (data not shown). LTβRfl/+ mice were born at expected Men-
delian frequencies, appeared healthy, and proofed fertile. To generate macrophage- and neutrophil-specific LTβR-deficient mice, LTβR<sup>flx/flx</sup> mice were crossed with LysM-Cre mice (32). Efficient cell type-specific deletion of the LTβR gene locus was verified by Southern blot analysis using BMDM (Fig. 1C). Expression of LTβR mRNA was efficiently ablated in BMDM of LTβR<sup>flx/flx × LysM-Cre</sup> mice compared with LTβR<sup>flx/flx</sup> control mice (Fig. 1D). Protein expression of the LTβR was strongly reduced in BMDM derived from LTβR<sup>flx/flx × LysM-Cre</sup> mice when compared with BMDM derived from LTβR<sup>flx/flx</sup> mice (Fig. 1E). This result was further substantiated by analyzing RPEC and bone marrow-derived neutrophils (BMDN) generated from both genotypes (data not shown). Collectively, these data indicate that LTβR expression was successfully inactivated on macrophages/neutrophils whereas LTβR expression was not altered in LTβR<sup>flx/flx</sup> mice.

**LTβR activation on macrophages/neutrophils induces TRIM30α expression**

The LTββLTβR pathway has been defined as being crucial for effective host defense (14, 16) and innate immune responses (18, 33). However, it is widely unknown which genes are controlled by LTβR signaling in vivo and which are critical for a controlled innate immune response. This issue was addressed by a comprehensive ex vivo microarray profiling of LTβR-dependent transcripts. Using this approach we were able to identify TRIM30α as a target gene of LTβR signaling (34).

So far, TRIM30α expression has only been shown to negatively regulate TLR-mediated NF-κB activation in BMDCs (29). Indeed, we found that in addition to LPS, stimulation of BMDM derived from wild-type mice with an agonistic anti-LTβR mAb induced TRIM30α mRNA expression (Fig. 2A). In contrast, in BMDM derived from LTβR-deficient mice no increase in TRIM30α mRNA expression could be detected (Fig. 2A). Examination of BMDM derived from LTβR<sup>flx/flx × LysM-Cre</sup> mice and control mice (LTβR<sup>flx/flx</sup>) revealed that cell type-specific ablation of LTβR expression on BMDM results in a strongly reduced ability to induce TRIM30α expression as a consequence of impaired LTβR signaling (Fig. 2B). A time course analysis of TRIM30α expression after LTβR activation on BMDM derived from wild-type mice revealed that TRIM30α mRNA expression is transiently induced as early as 8 h after LTβR stimulation, reaching a peak after 16 h stimulation (Fig. 2E). To evaluate TRIM30α protein expression in BMDM derived from wild-type, LTβR-deficient mice, LTβR<sup>flx/flx × LysM-Cre</sup> mice, and control mice (LTβR<sup>flx/flx)</sup> we used a TRIM30α-specific polyclonal antiserum and analyzed TRIM30α expression after LTβR activation by Western blot analysis. These results clearly demonstrate a transient LTβR-dependent induction of TRIM30α protein expression consistent with the pattern of its mRNA expression (Fig. 2C, 2D, 2F).

Interestingly, no TRIM30α protein expression was detected in BMDM derived from LTβR<sup>flx/flx × LysM-Cre</sup> mice after LTβR stimulation, supporting the observation of a strongly reduced TRIM30α mRNA induction in these cells (Fig. 2A, 2B). To test for a possible role of neutrophils in our experimental model using LTβR<sup>flx/flx × LysM-Cre</sup> mice, we assessed LTβR expression on neutrophils (Gr1<sup>+</sup>, CD11b<sup>+</sup>, and F4/80<sup>+</sup>) derived from bone marrow cells (BMDN) derived from both genotypes. Interestingly, only ~6% of the Gr1<sup>+</sup>, CD11b<sup>+</sup>, and F4/80<sup>+</sup> cell population isolated from bone marrow cells (BMDN) derived from LTβR<sup>flx/flx</sup> mice expressed LTβR on the cell surface. LTβR expression was ablated on neutrophils isolated from LTβR<sup>flx/flx × LysM-Cre</sup> mice (Fig. 2G). Examination of BMDN derived from LTβR<sup>flx/flx × LysM-Cre</sup> mice and control mice (LTβR<sup>flx/flx</sup>) revealed no significant induction of TRIM30α expression in both genotypes (Fig. 2H). Collectively, these data indicate that LTβR expression was successfully inactivated on BMDN derived from LTβR<sup>flx/flx × LysM-Cre</sup> mice, but no significant TRIM30α induction could be detected after LTβR stimulation in BMDN derived from LTβR<sup>flx/flx</sup> mice.

Furthermore, we investigated whether LTβR ligands (LTα1β2, LIGHT) expressed on activated CD4<sup>+</sup> T cells are capable of inducing TRIM30α expression by activating the LTβR on BMDM. Such a mechanism would require cell–cell contact and imply the possibility of a crosstalk between activated lymphocytes and macrophages. Cocultivation of different ratios of activated CD4<sup>+</sup> T cells with BMDM derived from wild-type mice results in an increasing induction of TRIM30α mRNA expression (Fig. 3A).

**FIGURE 1.** Conditional inactivation of the LTβR gene. (A and B) Generation of LTβR<sup>flx/flx</sup> mice. (A) Southern blot analysis of genomic DNA from E14.1 wild-type and targeted ES cells. Hybridization with the flanking probe yields a 17-kb fragment for the wild-type allele and a 4-kb fragment for the targeted allele. (B) PCR analysis of the integration of the 5’ loxp site after successful germline transmission. LTβR<sup>flx/flx</sup>, tail DNA from heterozygous mice; LTβR<sup>flx/flx × LysM-Cre</sup>, tail DNA from homzygous mice; Wt, tail DNA from control mouse. (C–E) Generation of macrophage/neutrophil-specific LTβR-deficient mice (LTβR<sup>flx/flx × LysM-Cre</sup>). (C) Southern blot analysis of LTβR gene deletion in BMDM. (D) Northern blot analysis of LTβR mRNA expression in BMDM derived from the indicated genotypes. (E) FACS analysis verifying the lack of LTβR protein expression on BMDM derived from LTβR<sup>flx/flx × LysM-Cre</sup> compared with the expression on LTβR<sup>flx/flx</sup> mice.
cells are currently under investigation. TRIM30 is induced in MyD88-deficient mice and tested TRIM30 activation and signaling or the activation of the MyD88 signaling pathway, we generated BMDM from both TNF-deficient and LTβR-deficient mice after pretreatment with a functional inhibitor of LTβR R activation induces TRIM30 signaling and 2) the MyD88 signaling pathway, indicating a unique activation (LTβR mAb) (Fig. 3A). To test whether LTβR-induced TRIM30α expression in BMDM is dependent on TNF expression and signaling or the activation of the MyD88 signaling pathway, we generated BMDM from both TNF-deficient and MyD88-deficient mice and tested TRIM30α induction after LTβR stimulation (Fig. 3B, 3C). We found that LTβR-mediated TRIM30α induction is independent of 1) TNF expression and signaling and 2) the MyD88 signaling pathway, indicating a unique LTβR-dependent signaling pathway in BMDM that subsequently induces the expression of TRIM30α. The exact mechanisms by which LTβR activation induces TRIM30α expression in myeloid cells are currently under investigation.

**LTβR activation on macrophages induces tolerance to TLR4 and TLR9 ligands**

To further confirm that LTβR activation on macrophages results in the induction of TRIM30α expression, we silenced TRIM30α expression by using siRNA in the mouse macrophage cell line J774, which we found positive for LTβR expression as revealed by RT-PCR and FACS analysis. Stimulation of J774 cells with agonistic anti-LTβR mAb (5G11, 10 μg/ml) in a time-dependent manner resulted in TRIM30α protein expression on BMDM derived from LTβR-deficient mice after stimulation with agonistic anti-LTβR mAb (5G11, 10 μg/ml) as control for 16 h. Data are expressed as means ± SD. Representative data from one out of two independent experiments are shown.

**FIGURE 2.** LTβR signaling induces TRIM30α expression in BMDM. (A and B) Quantitative RT-PCR analysis of TRIM30α induction in BMDM derived from wild-type mice and LTβR-deficient mice (A) or derived from LTβRflox/flox mice and LTβRflox/flox x LysM-Cre mice (B) after stimulation with LPS (100 ng/ml), agonistic anti-LTβR mAb (5G11, 10 μg/ml), or rat IgG (10 μg/ml) as control for 16 h. Data are expressed as means ± SD. Representative data from one out of three independent experiments are shown. (C and D) Western blot analysis of lysates of BMDM derived from wild-type mice and LTβR-deficient mice (C) or LTβRflox/flox mice and LTβRflox/flox x LysM-Cre mice (D) after stimulation with LPS (100 ng/ml), agonistic anti-LTβR mAb (5G11, 10 μg/ml), or rat IgG (10 μg/ml) as control for 16 h using a polyclonal anti-TRIM30α or anti-β-actin (loading control) antiserum. (E) Quantitative RT-PCR analysis of TRIM30α expression in BMDM derived from wild-type mice after stimulation with agonistic anti-LTβR mAb (5G11, 10 μg/ml) at indicated time points. Data are expressed as means ± SD. Representative data from one out of two independent experiments are shown. (F) Western blot analysis of BMDM derived from wild-type mice after stimulation with agonistic anti-LTβR mAb (5G11, 10 μg/ml) at indicated time points using a polyclonal anti-TRIM30α or anti-β-actin (loading control) antiserum. (G) FACS analysis of LTβR protein expression on BMDM derived from LTβRflox/flox x LysM-Cre mice compared with the expression on LTβRflox/flox mice. (H) Quantitative RT-PCR analysis of TRIM30α induction in BMDM derived from LTβRflox/flox mice and LTβRflox/flox x LysM-Cre mice after stimulation with LPS (100 ng/ml), agonistic anti-LTβR mAb (5G11, 10 μg/ml), or rat IgG (10 μg/ml) as control for 16 h. Data are expressed as means ± SD. Representative data from one out of two independent experiments are shown.
Subsequently, we tested whether TRIM30α expression induced by LTβR activation regulates the production of proinflammatory mediators. Large amounts of TNF and IL-6 are detectable in the supernatant of J774 cells after stimulation with LPS (TLR4) and CpG (TLR9) whereas stimulation of these cells with agonistic anti-LTβR mAb could not induce proinflammatory cytokine expression (Fig. 4C, 4D and data not shown). As expected, pretreatment of J774 cells with LPS results in a significant suppression of TNF and IL-6 expression. Interestingly, prestimulation of J774 cells with agonistic anti-LTβR mAb resulted in a significant suppression of TNF and IL-6 expression compared with J774 cells not prestimulated or cells prestimulated with rat IgG (Fig. 4C, 4D). Additionally, in restimulation experiments using LPS and IFN-γ, a highly reduced production of NO, a key mediator of the antimicrobial immune response, was observed when J774 cells were prestimulated with agonistic anti-LTβR mAb (data not shown). Furthermore, we observed a higher cytokine production in nonstimulated J774 cells when expressing TRIM30α-specific siRNA compared with J774 cells expressing scrambled siRNA. Again, prestimulation of J774 cells with agonistic anti-LTβR mAb resulted in a significant suppression of TNF and IL-6 expression when transfected with scrambled siRNA upon restimulation with LPS. In contrast, no suppression of TNF and IL-6 production was detected in J774 cells prestimulated with agonistic anti-LTβR mAb when TRIM30α expression was silenced using specific TRIM30α siRNA (Fig. 4C, 4D). These results clearly demonstrate that LTβR prestimulation results in the suppression of proinflammatory mediators upon TLR restimulation in a TRIM30α-dependent manner.

We next tested whether TRIM30α expression induced by LTβR activation regulates the production of proinflammatory cytokines and mediators in primary macrophages. Large amounts of TNF

FIGURE 3. LTβR-mediated TRIM30α expression induced by activated T cells is independent of TNF expression and the MyD88 signaling pathway. (A) Quantitative RT-PCR analysis of TRIM30α induction after coculturing of BMDM derived from wild-type mice or LTβR-deficient mice with activated CD4+ T cells isolated from wild-type or LTβRIgs/LIGHT double-deficient mice for 24 h. Additionally activated and LTβR-Ig-pretreated CD4+ T cells were incubated with BMDM derived from wild-type mice. Nonactivated CD4+ T cells were used as negative control. Data are expressed as means ± SD. Representative data from one out of two independent experiments are shown. (B and C) Quantitative RT-PCR analysis of TRIM30α induction in BMDM derived from wild-type mice and MyD88-deficient mice (B) or derived from wild-type mice and TNF-deficient mice (C) after stimulation with LPS (100 ng/ml), polyinosinic-polycytidylic acid (25 μg/ml) agonistic anti-LTβR mAb (5G11, 10 μg/ml), or rat IgG (10 μg/ml) as control. Data are expressed as means ± SD. Representative data from one out of three independent experiments are shown.

FIGURE 4. LTβR signaling inhibits the production of TNF and IL-6 by inducing TRIM30α expression. (A and B) Analysis of TRIM30α mRNA expression by quantitative RT-PCR (A) and TRIM30α protein expression by Western blot (B) in J774 cells after transfection (24 h) with TRIM30α-specific siRNA or scrambled siRNA followed by stimulation with agonistic anti-LTβR mAb (5G11, 10 μg/ml). (C and D) ELISA of TNF (C) or IL-6 (D) using supernatant of J774 cells transfected (24 h) with specific TRIM30α siRNA or scrambled siRNA before stimulated with agonistic anti-LTβR mAb (5G11, 10 μg/ml), rat IgG (10 μg/ml), or LPS (100 ng/ml) for 30 h followed by restimulation with LPS (100 ng/ml) for 8 h. Differences were considered significant with a p value of <0.05. **p < 0.001, ***p < 0.0001.
and IL-6 are detectable in the supernatant of BMDM derived from wild-type mice, LTβR<sup>+</sup> × LysM-Cre mice, or LTβR<sup>−/−</sup> mice after stimulation with TLR4 ligand (LPS) and TLR9 ligand (CpG), whereas stimulation with agonistic anti-LTβR mAb alone could not induce proinflammatory cytokine expression (Fig. 5A–D and data not shown). No difference in the induction of TLR tolerance was observed in BMDM derived from LTβR<sup>−/−</sup> mice or LTβR<sup>−/−</sup> mice using TLR4 and TLR9 agonists (data not shown). As expected, prestimulation of BMDM derived from LTβR<sup>−/−</sup> mice but not from LTβR<sup>−/−</sup> mice × LysM-Cre mice with agonistic anti-LTβR mAb resulted in hyporesponsiveness for the induction of TNF and IL-6 after restimulation with the TLR ligands LPS or CpG (Fig. 5A–D). These results were further verified by using BMDM derived from LTβR-deficient mice and wild-type mice (Supplemental Fig. 2A–D). Additionally, restimulation with LPS and IFN-γ resulted in a highly reduced production of NO when using BMDM derived from LTβR<sup>−/−</sup> mice cells prestimulated with agonistic anti-LTβR mAb in contrast to BMDM derived from LTβR<sup>−/−</sup> × LysM-Cre mice (Fig. 5E). Collectively, these data support the conclusion that LTβR activation on macrophages induces TRIM30α expression, which renders these cells hyporesponsive with respect to proinflammatory cytokine and mediator expression.

**LTβR activation on macrophages induces TLR4 tolerance in vivo**

To further characterize the function of LTβR-induced TRIM30α expression in vivo we made use of the LPS-induced tolerance model. Pretreatment of wild-type mice with low doses of LPS on day 5 and day 3 before LPS rechallenge resulted in strongly reduced TNF serum levels compared with wild-type mice pretreated with PBS or rat IgG. Interestingly, pretreatment with agonistic anti-LTβR mAb also resulted in strongly reduced TNF serum levels after LPS rechallenge comparable to the levels observed after the pretreatment with low doses of LPS. This effect was abolished when using inactivated agonistic anti-LTβR mAb, thus excluding a possible LPS contamination of the Ab preparation (Supplemental Fig. 2E). Furthermore, LTβR-deficient mice were no longer able to mount a LPS tolerance induction by the treatment with anti-LTβR mAb, although reduced TNF serum levels were detected by pretreatment of these mice with low doses of LPS before LPS rechallenge (Supplemental Fig. 2F). The analysis of LTβR<sup>−/−</sup> × LysM-Cre mice in our experimental model demonstrated that pretreatment with agonistic anti-LTβR mAb does not result in reduced TNF serum levels, suggesting that LTβR signaling in macrophages seems to be involved in TLR tolerance in our experimental model (Fig 6B). As anticipated, pretreatment of the LTβR in LTβR<sup>−/−</sup> mice resulted in strongly reduced TNF serum levels, comparable to levels detected after pretreatment with low doses of LPS (Fig. 6A) or observed after LPS pretreatment of wild-type mice (Supplemental Fig. 2E). Whereas in both LTβR<sup>−/−</sup> × LysM-Cre mice and LTβR<sup>−/−</sup> mice LPS induces TRIM30α expression, the stimulation of LTβR<sup>−/−</sup> mice with agonistic anti-LTβR mAb results in the upregulation of TRIM30α mRNA expression, and no induction of TRIM30α mRNA was detected in LTβR<sup>−/−</sup> × LysM-Cre mice (Fig. 6C). This observation matches our additional findings of TRIM30α induction after stimulation with agonistic anti-LTβR mAb in LTβR-deficient mice (Supplemental Fig. 2G). These results clearly demonstrate that LTβR signaling in macrophages

**FIGURE 5.** LTβR activation on BMDM results in the suppression of proinflammatory mediators upon TLR4 and TLR9 restimulation. (A–E) TNF (A, C), IL-6 (B, D), or NO production (E) in the supernatant of BMDM derived from LTβR<sup>−/−</sup> × LysM-Cre mice stimulated with agonistic anti-LTβR mAb (5G11, 10 μg/ml) or rat IgG (10 μg/ml) for 30 h before restimulation with LPS (100 ng/ml) (A, B), CpG (1 μM) for 8 h (C, D), or LPS (200 ng/ml) and IFN-γ (20 ng/ml) for 24 h (E). Data are expressed as mean ± SD. Statistical significance was determined using a Student t test. Differences were considered significant with a p value of <0.05. **p < 0.001, ***p < 0.0001. Representative data from one out of three independent experiments are shown.
induces TRIM30α expression, which subsequently results in tolerance to the TLR4 ligand in vivo.

Discussion
Most studies on LTβR signaling have focused on the organization, development, and maintenance of lymphoid tissues and their role in adaptive immune responses (7). Our data demonstrate that LTβR signaling is very important for the control of innate immune reactions by inducing a negative feedback mechanism in myeloid cells while mounting the early innate immune response. LTβR-mediated induction of TRIM30α seems to be tightly controlled on mRNA as well as on the protein level, resulting in the suppression of proinflammatory cytokine and mediator expression in vitro and in vivo.

In addition to LTβR activation using an agonistic anti-LTβR mAb or activated CD4+ T cells expressing LTβR ligands, we also found that recombinant mouse LIGHT was capable of inducing TRIM30α expression in BMDM in vitro (data not shown). So far, LIGHT has been described as a costimulatory cytokine in T cell activation by interacting mainly with HVEM expressed on T cells (23, 35), but it is not yet known whether the interaction with the LTβR contributes to TRIM30α induction in vivo.

Although activation of TLR-mediated signaling pathways initiating an early inflammatory response are indispensable for protecting the host against pathogenic organisms, an excessive and/or prolonged activation may lead to both acute and chronic inflammatory diseases. Therefore, the intensity and duration of TLR responses must be tightly regulated. Downregulation of TLR signaling, called TLR tolerance, as well as cross-tolerance among various TLR ligands might have been developed to prevent excessive inflammatory damage to the host. Most likely TLR tolerance is achieved through multiple mechanisms involving the induction of negative regulators such as A20, IRAK-M, MyD88, as well as SOCS-1 (36–38). However, these negative regulators mediating self and cross-tolerance are induced by TLR signaling pathways. Based on our observation that activated lymphocytes expressing LTβR ligands induce TRIM30α expression in myeloid cells, it is tempting to speculate that activated lymphocytes as part of the adaptive immune response interact and communicate with myeloid cells to induce a signaling pathway that negatively regulates the early innate inflammatory response.

TRIM30α is a member of the TRIM superfamily, many of which are expressed upon TLR activation and in an IFN-γ-dependent manner (39, 40). It has been shown that members of the TRIM superfamily are involved in a broad range of biological processes that are associated with innate immune reactions (41). A recent study showed that TRIM30α interacts with TAK1 and promotes the degradation of TAB2 and TAB3, resulting in an inhibition of NF-κB activation and consequently the inhibition of NF-κB-dependent inflammation (29). Because TAK1 plays a crucial role in NF-κB activation through other signaling pathways such as those initiated by TNF and IL-1 (42), TRIM30α might also play a role in regulating inflammatory responses in addition to those initiated by TLR activation.

A functional ortholog to TRIM30α in humans has not yet been identified based on sequence similarity; however, a similar pathway seems to operate in human cells. Using the human monocyte cell line THP-1 we were able to induce LTβR-mediated TLR tolerance (data not shown), suggesting that some proteins seem to regulate proinflammatory cytokine and mediator expression in an LTβR-dependent manner in human cells of myeloid origin.

The exact molecular mechanisms by which LTβR induces TRIM30α expression in myeloid cells are currently under investigation; however, within this study, using a novel conditional LTβR mouse line, important information on the role of LTβR/
TRIM30b actions could be provided that is essential for protection against an exacerbating inflammatory immune response.

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Disclosures

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