Gene expression induced by Toll-like receptors in macrophages requires the transcription factor NFAT5

Maria Buxadé,1 Giulia Lunazzi,1 Jordi Minguillón,1 Salvador Iborra,2 Rosa Berga-Bolaños,1 Margarita del Val,2,3 José Aramburu,1 and Cristina López-Rodriguez1

Toll-like receptors (TLRs) engage networks of transcriptional regulators to induce genes essential for antimicrobial immunity. We report that NFAT5, previously characterized as an osmostress responsive factor, regulates the expression of multiple TLR-induced genes in macrophages independently of osmotic stress. NFAT5 was essential for the induction of the key antimicrobial gene Nos2 (inducible nitric oxide synthase [iNOS]) in response to low and high doses of TLR agonists but is required for Tnf and Il6 mainly under mild stimulatory conditions, indicating that NFAT5 could regulate specific gene patterns depending on pathogen burden intensity. NFAT5 exhibited two modes of association with target genes, as it was constitutively bound to Tnf and other genes regardless of TLR stimulation, whereas its recruitment to Nos2 or Il6 required TLR activation. Further analysis revealed that TLR-induced recruitment of NFAT5 to Nos2 was dependent on inhibitor of κB kinase (IKK) β activity and de novo protein synthesis, and was sensitive to histone deacetylases. In vivo, NFAT5 was necessary for effective immunity against Leishmania major, a parasite whose clearance requires TLRs and iNOS expression in macrophages. These findings identify NFAT5 as a novel regulator of mammalian anti-pathogen responses.

Abbreviations used: BMDM, BM-derived macrophage; ChIP, chromatin immunoprecipitation; CHX, cycloheximide; HDAC, histone deacetylase; IKK, inhibitor of κB kinase; iNOS, inducible nitric oxide synthase; IRF, IFN regulatory factor; MAP, mitogen-activated protein; poly I:C, polyinosinic: polycytidylic acid; RT-qPCR, real-time quantitative PCR; TLR, Toll-like receptor; TSA, trichostatin A.

Toll-like receptors (TLRs) belong to a large group of sensors specialized in recognizing specific molecular patterns of pathogens and are expressed by sentinel cells of the immune system such as dendritic cells and macrophages (West et al., 2006; O’Neill and Bowie, 2007). Upon recognition of specific ligands, TLRs initiate intracellular signaling cascades that induce a broad gene expression program that regulates the defense against pathogens and stimulates adaptive immune responses (Jenner and Young, 2005; West et al., 2006; O’Neill and Bowie, 2007). The different TLRs ensure an effective response against a wide variety of microbial pathogens by inducing a common set of gene products with general antimicrobial and immunomodulatory properties (Jenner and Young, 2005).

This is accomplished through the shared use of core signaling pathways in which mitogen-activated protein (MAP) kinases (p38, JNK, and ERK1/2), the inhibitor of κB kinase (IKK) β–NF-κB axis, and IFN regulatory factor (IRF) transcription factors are prominent players (Dong et al., 2002; Honda and Taniguchi, 2006; West et al., 2006). In addition, TLRs need precise regulatory mechanisms to adjust the patterns of genes expressed and their magnitude of induction to variables such as the type of ligand, the transient or persistent nature of the stimulation, the dose of that stimulus, or the effect of tolerance (Foster et al., 2007; Litvak et al., 2009).

Specificity and fine tuning of gene expression downstream TLRs are achieved through
various strategies. A central component in control of specificity is the mobilization of combinations of transcriptional regulators that are either constitutively functional or become expressed and/or activated upon TLR stimulation (Medzhitov and Horng, 2009). For instance, NF-κB factors respond to all TLRs, but they participate in different aspects of these responses by cooperating with other transcriptional regulators, such as IRF3 (Wietek et al., 2003) and E2F1 (Lin et al., 2007), or by controlling their expression, as described for C/EBPβ (Litvak et al., 2009) and JMJD3 (De Santa et al., 2007). Another component accounting for TLR-induced specific gene expression in response to pathogens is the dynamic remodeling of chromatin architecture, and the recruitment of diverse co-activator and co-repressor complexes with histone-modifying activity that occurs at the regulatory regions of certain genes (Weinmann et al., 1999; Ramirez-Carrozza et al., 2006; Hargreaves et al., 2009; Ramirez-Carrozza et al., 2009; Glass and Saigo, 2010). According to their transcriptional requirements, TLR-induced genes were recently classified in three main categories (Saccani et al., 2001; Ramirez-Carrozza et al., 2006; Hargreaves et al., 2009; Ramirez-Carrozza et al., 2009). Early primary response genes, such as Tnf, Pgs2, and Njkha1, usually contain CpG island promoters, are expressed rapidly and independently of SWI/SNF-induced nucleosome remodeling or de novo protein synthesis, and are constitutively assembled into a chromatin structure similar to that found in active genes. Late primary response genes, such as Cdl5 and Cdl2, are also induced independently of de novo protein expression but require chromatin remodeling. Finally, induction of secondary response genes, such as Nos2, Il12b, and Il6, depends on de novo protein synthesis and often requires SWI/SNF-dependent nucleosome remodeling.

Although these studies have revealed general mechanistic principles underlying gene expression downstream of TLRs, and substantial knowledge on the transcriptional network acting in TLR responses has been gathered in recent years, our current map of the identity and specific functions of the transcriptional regulators involved is still incomplete. Increased knowledge on immune defense mechanisms that control gene expression during the activation of TLRs is necessary to understand how host and parasite factors might predispose individuals to develop the disease or control the infection, and may also provide new opportunities for therapeutic intervention.

The transcription factor NFAT5 belongs to the family of Rel-like domain-containing factors, which comprises the NF-κBIs and the calcineurin-dependent NFATc proteins (López-Rodríguez et al., 1999b, 2001; Miyakawa et al., 1999; Aramburu et al., 2006). NFAT5 uses a dimerization mechanism conserved in NF-κB proteins (López-Rodríguez et al., 1999a, 2001; Stroud et al., 2002) and, although its function is not dependent on the calcium-activated phosphatase calcineurin, NFAT5 recognizes DNA elements whose sequence coincides with that of sites bound by NFATc proteins (Rao et al., 1997; López-Rodríguez et al., 1999b; Stroud et al., 2002). NF-κB and NFATc proteins are involved in innate immune responses activated upon recognition of specific pathogen-associated molecular patterns by different types of receptors. NF-κB proteins have a broad impact in the induction of gene expression in the response to pathogens because they are positioned downstream of TLRs, RIG-I-like receptors, and certain members of the NOD-like receptors and C-type lectin receptors families (Meylan et al., 2006; Kawai and Akira, 2007; Geijtenbeek and Gringhuis, 2009). In contrast, and also in the context of innate responses, NFATc proteins are not activated by TLRs but respond to the calcium mobilization-coupled receptors Dectin 1 and CD14 (Goodridge et al., 2007; Zanoni et al., 2009; Greenblatt et al., 2010). NFAT5 is a central regulator of gene expression in the adaptation to extracellular hypertonicity (Aramburu et al., 2006; Jeon et al., 2006), a function which is controlled by the p38 MAP kinase (Ko et al., 2002; Morancho et al., 2008). In contrast to NF-κB and NFATc proteins, an immunological role for NFAT5 has remained elusive beyond its osmoregulatory function in leukocytes (Go et al., 2004; Morancho et al., 2008; Drews-Elder et al., 2009; Kino et al., 2009; Machnik et al., 2009; Berga-Bolaños et al., 2010). However, NFAT5 can induce the expression of several pro-inflammatory cytokines, growth factors, and surface receptors in lymphocytes and macrophages exposed to hyperosmotic stress (López-Rodríguez et al., 2001; Kino et al., 2009; Machnik et al., 2009; Berga-Bolaños et al., 2010; Roth et al., 2010). The ability of NFAT5 to induce genes with immunomodulatory activity and not restricted to osmoadaptation led us to consider that, similarly to other Rel-like transcription factors, it might play a role in specific immune receptor-mediated responses.

We report that NFAT5 regulates TLR-induced gene expression in primary macrophages, and that this capacity is independent of its osmoregulatory function. NFAT5-regulated genes encode, among others, for cytokines and chemokines, extracellular matrix or protease-related proteins, regulators of nitric oxide production, proteins that control cell cycle progression and proliferation, and certain repressors of inflammation. NFAT5 was particularly required for the induction of genes, such as Tnf and Il6, by low doses of TLR ligands, but essential for the expression of Nos2 (inducible nitric oxide synthase [iNOS]) under both low and high doses of stimulus, suggesting that NFAT5 enables macrophages to modulate specific gene expression profiles in response to different stimulation thresholds. Whereas NFAT5 was expressed in unstimulated macrophages, it was further induced in an NF-κB–dependent manner upon TLR stimulation, indicating that although basal levels of NFAT5 could suffice to induce certain target genes, its long-term accumulation might contribute to sustain the prolonged expression of others. We found that NFAT5 exhibited two modes of association with target genes, as it was constitutively bound to Tnf and other genes regardless of TLR stimulation, whereas its recruitment to Nos2 or Il6 required TLR activation. Further analysis revealed that the recruitment of NFAT5 to Nos2 was dependent on IKKβ activity and de novo protein synthesis, and was sensitive to histone deacetylases (HDACs). These results indicated that NFAT5 is poised to react as a primary response factor for a subset of genes, but subordinated to secondary
NFAT5 regulates gene expression in macrophages in response to TLRs.

Rel-like transcription factors play essential roles in the innate defense against pathogens. Because NFAT5 is expressed in leukocytes and regulates the expression of diverse immunomodulatory proteins in response to osmotic stress, we asked whether it could participate in the transcriptional response induced by specific pathogen receptors. We began by analyzing whether lack of NFAT5 in macrophages affected the TLR-mediated induction of diverse primary and secondary response proinflammatory and antimicrobial genes.

**RESULTS**

NFAT5 regulates gene expression in macrophages in response to TLRs. Rel-like transcription factors play essential roles in the innate defense against pathogens. Because NFAT5 is expressed in leukocytes and regulates the expression of diverse immunomodulatory proteins in response to osmotic stress, we asked whether it could participate in the transcriptional response induced by specific pathogen receptors. We began by analyzing whether lack of NFAT5 in macrophages affected the TLR-mediated induction of diverse primary and secondary response proinflammatory and antimicrobial genes.
The experiments mentioned in the previous paragraph indicated that NFAT5 was required for the expression of a group of TLR-induced genes. To get a broader view of NFAT5-regulated genes, we performed RNA microarray analysis of BMDMs stimulated with LPS during 6 h, which showed that from a total of 755 genes induced more than twofold by LPS, at least 83 were regulated by NFAT5 (Fig. 1 E; and Table S1). Of these, 24 were induced between 4-fold and >100-fold in WT macrophages, and their expression was reduced by >65% in NFAT5-deficient cells (Table S1). These genes encoded, among others, for diverse proteins such as cytokines and chemokines, extracellular matrix or protease-related proteins, regulators of nitric oxide production, regulators of cell cycle progression and proliferation, and certain repressors of inflammation (Fig. 1 E), which indicates that NFAT5 might be relevant in various aspects of the response to pathogens.

Analysis of Nfat5−/− BMDMs did not reveal defects in their maturation and capacity to activate main signaling pathways downstream of TLRs, including IRF3 dimerization, IκBα degradation, and phosphorylation of JNK, ERK, or p38 MAP kinases (Fig. S2, A–C), indicating that the specific gene expression defects observed in NFAT5-deficient BMDMs were not the result of a general impairment of TLR signaling. As NFAT5 can be activated by hypertonic stress in macrophages (Morancho et al., 2008; Machnik et al., 2009), we confirmed that culture media remained isotonic during their maturation from BM cells and after LPS stimulation, and that BMDMs were severely impaired in their expression of Nos2, Il6, and Ptgs2 mRNAs in response to LPS (Fig. 1 A). Induction of Tnf and Il12b was less affected, and the induction of Ccl5 mRNA was delayed (Fig. 1 A). Therefore, NFAT5 regulated the expression of genes with fast induction kinetics, such as Tnf, as well as genes with a slower and more gradual induction (Nos2 and Il6). In these experiments, we used low concentrations of TLR agonists to avoid the activation of TLR-independent pathways (Liu et al., 2001; Gitlin et al., 2006). In this regard, defects in Il6 expression observed in Nfat5−/− BMDMs were more evident at 0.3 ng/ml LPS than at 1 ng/ml of LPS, whereas Nos2 induction was substantially impaired in response to either dose (Fig. 1 B). Consistent with the mRNA data, TLR-activated production of iNOS, IL-6, and TNF proteins was decreased in Nfat5−/− macrophages, and defects in IL-6 and TNF induction were more pronounced at low doses of LPS (Fig. 1, C and D). Impaired iNOS expression was also observed when NFAT5-deficient BMDMs were stimulated with LPS plus IFN-γ (Fig. S1 C), which synergize to induce iNOS transcription (Xie et al., 1993).

The experiments mentioned in the previous paragraph indicated that NFAT5 was required for the expression of a group of TLR-induced genes. To get a broader view of NFAT5-regulated genes, we performed RNA microarray analysis of BMDMs stimulated with LPS during 6 h, which showed that from a total of 755 genes induced more than twofold by LPS, at least 83 were regulated by NFAT5 (Fig. 1 E; and Table S1). Of these, 24 were induced between 4-fold and >100-fold in WT macrophages, and their expression was reduced by >65% in NFAT5-deficient cells (Table S1). These genes encoded, among others, for diverse proteins such as cytokines and chemokines, extracellular matrix or protease-related proteins, regulators of nitric oxide production, regulators of cell cycle progression and proliferation, and certain repressors of inflammation (Fig. 1 E), which indicates that NFAT5 might be relevant in various aspects of the response to pathogens.

Analysis of Nfat5−/− BMDMs did not reveal defects in their maturation and capacity to activate main signaling pathways downstream of TLRs, including IRF3 dimerization, IκBα degradation, and phosphorylation of JNK, ERK, or p38 MAP kinases (Fig. S2, A–C), indicating that the specific gene expression defects observed in NFAT5-deficient BMDMs were not the result of a general impairment of TLR signaling. As NFAT5 can be activated by hypertonic stress in macrophages (Morancho et al., 2008; Machnik et al., 2009), we confirmed that culture media remained isotonic during their maturation from BM cells and after LPS stimulation, and that BMDMs...
expressed osmoresponsive genes only when exposed to hypertonicity and not in response to TLRs (Fig. S3, A–C and Table S1). Therefore, NFAT5 was required for the expression of multiple TLR-responsive genes in macrophages in a hypertonicity-independent manner.

Constitutive and TLR-induced association of NFAT5 with target genes

Several NFAT5-regulated genes, which included primary and secondary TLR-response genes (Ramírez–Carrozzi et al., 2009), contained clear consensus NFAT5 binding sites in their regulatory regions (5′- (T/C/A)GGAAA-3′; López-Rodríguez et al., 1999b; Fig. S4 A). Chromatin immunoprecipitation (ChIP) experiments showed that NFAT5 was recruited to the Nos2 promoter after stimulation of BMDMs with LPS or poly I:C (Fig. 2 A; and Fig. S4 B). Similarly, NFAT5 was recruited to the regulatory regions of other secondary response genes such as Il6 or Il12b in a TLR-dependent manner (Fig. 2 A; and Fig. S4 B). Binding of NFAT5 to Ptgds2, a gene with a biphasic primary and secondary response behavior (Caivano et al., 2001), also required TLR stimulation (Fig. 2 A). In contrast, NFAT5 was constitutively bound to the Tif1 gene promoter regardless of TLR stimulation (Fig. 2 B and Fig. S4 B), possibly reflecting that Tif1 is an early primary response gene that in resting conditions is already associated with certain transcription factors and chromatin remodeling complexes (Ramírez–Carrozzi et al., 2006; Hargreaves et al., 2009). This pattern of constitutive NFAT5 binding was also observed in other primary response target genes (Il1a, Traf1, and Cld2; Fig. 2 B), but not in the primary response gene Csf2, to which NFAT5 was recruited in a TLR-dependent manner (Fig. 2 B). Binding of NFAT5 to the proximal promoter of target genes such as Csf2, Mmp13, or Lcn2 was not detected, indicating that it might regulate other regions or contribute indirectly to their expression. As specificity controls for the ChIP assay, preimmune rabbit serum did not immunoprecipitate any of those regulatory regions or contribute indirectly to their expression. As specificity controls for the ChIP assay, preimmune rabbit serum did not immunoprecipitate any of those regulatory regions or contribute indirectly to their expression.
binding sites (López-Rodríguez et al., 2001; Fig. 2 A; and Fig. S4 B). Altogether, our data indicated that NFAT5 exhibited two general patterns of association with its direct target genes in macrophages: it was constitutively bound to most primary response target genes in unstimulated macrophages, but its recruitment to secondary response genes required TLR activation.

**NFAT5 regulates the TLR-induced activation of the Nos2 promoter**

Given that iNOS induction by TLRs was severely impaired in NFAT5-deficient BMDMs, we analyzed the direct regulation of the Nos2 gene promoter by NFAT5 in RAW 264.7 macrophage cells. Two independent NFAT5-specific shRNAs (shN5-1 and shN5-2), whose effectiveness we had previously validated with an osmopressor-responsive, NFAT5-dependent reporter (Fig. 3 A), inhibited the activation of the iNOS-Luc reporter by LPS (Fig. 3 B). Likewise, mutation of the NFAT5 binding site in iNOS-Luc abrogated its responsiveness to LPS (Fig. 3 C). Suppression of NFAT5 also impaired the activation of the iNOS reporter by agonists of different TLRs (Fig. 3 D) and prevented iNOS expression as well as nitric oxide production (Fig. 3, E and F). These findings, together with our previous ChIP results, showed that NFAT5 is a direct regulator of iNOS transcription, and further supported the interpretation that defective gene expression in NFAT5-deficient macrophages activated by TLRs was specifically a result of the lack of this factor.

**TLR-induced NFAT5 expression is regulated by the IKKβ–NF-κB pathway**

Activation of TLRs induced a progressive accumulation of NFAT5 protein that was preceded by an increase in its mRNA (Fig. 4, A and B) and was dependent on transcription because it was blunted by the RNA synthesis inhibitors actinomycin D and α-amanitin (Fig. 4 C). The accumulation of NFAT5 protein increased slowly in response to TLRs (Fig. 4 B), and during the first 2 h its abundance was largely insensitive to cycloheximide (CHX), whereas by 4 h a more substantial CHX-sensitive accumulation, suggestive of de novo synthesis, was observed (Fig. 4 D). These results suggested that basal levels of preexisting NFAT5 might be sufficient to initiate expression of genes with fast induction kinetics, such as Tnf, whereas its sustained accumulation at later time points could contribute to prolong the expression of genes with slower induction kinetics, like Nos2.

The oscillatory pattern of NFAT5 mRNA induction in TLR-stimulated macrophages was reminiscent of NF-κB-regulated genes (Hoffmann et al., 2002) and led us to examine whether this factor might control NFAT5 expression. Analysis of the Nfat5 gene revealed two clear NF-κB consensus binding sites upstream of Nfat5 exon 1 that were remarkably conserved across several mammalian species (Fig. 4 E). ChIP experiments showed that p65 (p65/NF-κB) was readily recruited to these sites upon TLR activation (Fig. 4 E). Moreover, TLR-induced accumulation of Nfat5 mRNA was blunted upon inactivation of IKKβ with two independent pharmacological inhibitors, BAY 11–7082 and BMS-345541, to an extent comparable to that of blocking transcription (Fig. 4 F). In addition, pharmacological and genetic inactivation of IKKβ prevented the long-term accumulation of NFAT5 in response to TLRs, but inhibition of other TLR-activated pathways, such as p38, ERK, JNK, PI3K, and mTOR, did not affect it (Fig. 4, G and H). Altogether, these data indicated that de novo expression of NFAT5 after TLR activation required NF-κB–dependent transcription.

**Different mechanisms regulate the TLR-induced recruitment of NFAT5 to its target genes**

Our results showed that, although NFAT5 was constitutively bound to target genes that are independent of TLR-induced chromatin remodeling, it required TLR stimulation to be recruited to most targets that are expressed upon chromatin remodeling. In this regard, TLR-induced binding of NFAT5 to Nos2 could be detected after 30 min of stimulation and reached a maximum by 2 h (Fig. 5 A). Because this rapid recruitment occurred before any substantial accumulation of newly synthesized NFAT5 (Fig. 4, B and D), it could be used to monitor the effect of different TLR-activated signals on the specific recruitment of NFAT5 to its targets. We observed that binding of NFAT5 to the Nos2 promoter, induced by a 2-h LPS stimulation, was sensitive to inhibition of IKKβ using two chemically unrelated pharmacological inhibitors (Fig. 5 B). Confirmation of the dependence of NFAT5 recruitment to Nos2 on IKKβ was obtained using IKKβ-deficient BMDMs, in which the LPS-induced binding of NFAT5 to the Nos2 promoter was significantly reduced, to a similar extent as the decrease in p65 activation (Fig. 5 C and Fig. S5 A). In contrast, the constitutive association of NFAT5 with Tnf was maintained in LPS-treated IKKβ-deficient macrophages (Fig. 5 C). We also observed that inhibition of the MAP kinases p38, ERK, and JNK did not prevent the TLR-induced binding of NFAT5 to Nos2 (Fig. 5 D). Because p38 is a major activator of NFAT5 in osmopressor responses (Ko et al., 2002; Moranchón et al., 2008), this result indicated that NFAT5 binding to TLR- or osmopressor-responsive genes likely involved different mechanisms.

LPS-induced expression of iNOS involves a rapid, NF-κB–dependent removal of repressor complexes associated with HDACs from the Nos2 promoter (Ogawa et al., 2004; Pascual et al., 2005; Huang et al., 2009). Moreover, although it has not been specifically determined for Nos2, TLR-induced chromatin remodeling in other secondary response genes depends on de novo protein synthesis (Weinmann et al., 1999; Ramírez-Carrozzi et al., 2006). Therefore, we analyzed whether the TLR-induced recruitment of NFAT5 to genes such as Nos2 was also sensitive to de novo protein synthesis and HDAC activity. We observed that binding of NFAT5 to Nos2 and Il12b was decreased by blockade of protein synthesis with CHX in LPS-stimulated cells (Fig. 5 E). In contrast, its constitutive association with the primary response genes Tnf and Cd2 was not affected by CHX (Fig. 5 E), and, moreover,
Figure 4. Involvement of the IKKβ–NF-κB pathway on the expression of NFAT5 in response to TLRs. (A) Quantification of NFAT5 mRNA upon stimulation of BMDMs with 10 µg/ml pIC or 10 ng/ml LPS for the indicated times. mRNA content was measured by RT-qPCR, normalized to L32 mRNA, and is shown relative to unstimulated cells, which was given an arbitrary value of 1. (B) Expression of NFAT5 in BMDMs stimulated with 1 µg/ml pIC or 1 ng/ml LPS for the indicated times was analyzed by Western blot. α-Tubulin is shown as loading control. (C) Western blot for NFAT5 in BMDMs left untreated (−), or stimulated with 10 ng/ml LPS (20 h) after 1 h of pretreatment with actinomycin D (ActD) or α-amanitin (α-Ama) at the indicated concentrations. Pyruvate kinase (PyrK) is shown as loading control. (D) Western blot for NFAT5 in BMDMs treated with 0.5 µg/ml CHX, 1 ng/ml LPS, or both during different times (CHX was added 30 min before LPS). To ensure the complete extraction of NFAT5 from cells we used urea-based whole-cell lysates. α-Tubulin was used as loading control. (E) Schematic representation of the promoter region of the Nfat5 gene. Consensus binding sites for NF-κB (capital letters) and flanking sequences are shown for human, dog, mouse, and pig genomes. CpG-rich designate a CpG island, and the small bar under the NF-κB binding sites in the diagram shows the region amplified by the primers used in the ChIP experiments. The bottom panels show the ChIP analysis of NF-κB (p65) binding to the Nfat5 promoter or an irrelevant region (exon 14 of the Nfat5 gene) in BMDMs left untreated (−) or stimulated with 10 ng/ml LPS for 2 or 4 h. A control rabbit IgG (Ig) was included as negative control. Immunoprecipitated chromatin was analyzed by RT-qPCR and normalized to its respective total chromatin (input). Graphics represent the enrichment in chromatin immunoprecipitated by the NF-κB–specific antibody relative to the immunoprecipitation with the control IgG in unstimulated cells (which was given an arbitrary value of 1). (F) NFAT5 mRNA levels in BMDMs stimulated during 2 h with 10 µg/ml pIC or 10 ng/ml LPS without or with a 1-h pretreatment with 10 µM BAY 11–7082, 2 µM BMS-345541, or 0.1 µg/ml actinomycin D (ActD). (G) Western blot for NFAT5 in BMDMs left untreated (−), or stimulated with 10 ng/ml LPS for 20 h without inhibitors or with a 1-h pretreatment with 10 µM BAY 11–7082, 2 µM BMS-345541, 10 µM SB202190, 10 µM PD98059, 10 µM SP600125, 1 µM dexamethasone, 20 µM LY294002, or 200 nM rapamycin. DMSO and ethanol (EtOH) are vehicle controls. (H) Western blot for NFAT5 in WT (IKKβ−/−) and IKKβ-deficient (IKKβ−/−) BMDMs left untreated (−) or stimulated with 10 ng/ml LPS for 15 h. Graphics in A, E, and F correspond to the mean ± SEM of three independent experiments (*, P < 0.05; **, P < 0.01). Results in B, C, D, G, and H are representative of three independent experiments.
NFAT5 appeared capable of enhancing the induction of Tnf mRNA despite blockade of protein synthesis because CHX-treated WT macrophages induced it better than NFAT5-deficient ones (Fig. S5 B). In the same experiments, CHX abrogated the induction of Nos2 mRNA (Fig. S5 B). Altogether, these results indicated that preexisting, promoter-bound NFAT5 could enhance the transcription of genes such as Tnf without additional protein synthesis, whereas the inducible recruitment of NFAT5 to other genes, like Nos2, required de novo protein synthesis and IKKβ activity.

We then tested the effect of the HDAC inhibitor trichostatin A (TSA) on the chromatin-binding capacity of NFAT5. TSA induced the binding of NFAT5 to the Nos2 promoter in unstimulated macrophages nearly as efficiently as LPS stimulation (Fig. 5 F). Similarly, association of NFAT5 with the Il12b enhancer was induced by TSA in unstimulated macrophages. These observations indicated that, in the absence of TLR stimulation, inhibition of HDACs sufficed to induce the association of NFAT5 with target genes whose expression requires chromatin remodeling. Although it cannot be ruled out that TSA could cause other effects in addition to inhibiting histone deacetylation, this result lends support to the concept that inhibition of HDACs, which occurs upon TLR activation (Glass and Saijo, 2010), could favor the recruitment of NFAT5 to genes such as Nos2. Altogether, our results indicate that recruitment of NFAT5 to these genes might be sensitive to TLR-induced changes in chromatin configuration involving IKKβ–NF-κB, de novo protein synthesis, and HDAC inhibition.

In vivo response of NFAT5-deficient mice to L. major infection
We next sought to determine the impact of NFAT5 deficiency on the in vivo response against L. major infection, a model in which pathogen clearance requires different TLRs normalized to its respective total chromatin (input). The anti-NFAT5–immunoprecipitated chromatin in cells stimulated with 1 ng/ml LPS was used as reference sample and given an arbitrary value of 100%. (F) As in E, but cells were left untreated or treated as indicated with TSA for 5 h, or stimulated with 10 ng/ml LPS for 2 h. The enrichment in chromatin immunoprecipitated by the NFAT5-specific antibodies is represented relative to the amount immunoprecipitated by the NFAT5 antibodies upon LPS stimulation (which was given an arbitrary value of 100%). Graphics show the mean ± SEM of three (A, B, C, E, and F) or four (D) independent experiments (*, P < 0.05; **, P < 0.01).
Figure 6. In vivo response of NFAT5-deficient mice to L. major infection. (A) Intracellular iNOS expression in macrophages from the footpads of WT (left) and NFAT5-deficient (right) mice after infection with L. major. Mice were injected with PBS (filled histogram) or inoculated with 5 × 10⁶ L. major parasites (thick line histogram) in the footpad. After 24 h, cell suspensions from the skin were stained with antibodies to F4/80 and iNOS, and analyzed by flow cytometry. The dotted line represents the staining with an isotype control antibody. A representative experiment of a total of eight performed (each footpad from four mice of each group, WT and KO) is shown. (B) As in A, but the median intensity of fluorescence (MFI) of intracellular iNOS staining in F4/80⁺ macrophages is represented at the indicated time points. The mean ± SEM of four mice per group is shown. For the 0-h time point, the MFI values for intracelular iNOS correspond to PBS injection. (C and D) Parasite load was determined in the locally infected skin and draining lymph node (dLN), 72 h after high-dose infection in the footpad (C) or 3 wk after low-dose infection in the ear (D). The parasite burden for each individual mouse is depicted in logarithmic scale (Log_{10}). The horizontal bars represent the mean values for each group: (C) footpads (Nfat5⁺/⁺ n = 12 and Nfat5⁻/⁻ n = 16) and popliteal dLN (Nfat5⁺/⁺ n = 6 and Nfat5⁻/⁻ n = 8); (D) ears (Nfat5⁺/⁺ n = 30 and Nfat5⁻/⁻ n = 20) and retromaxillar dLN (Nfat5⁺/⁺ n = 15 and Nfat5⁻/⁻ n = 10). (E) Analysis of parasite dissemination after L. major infection. The graph represents the quantification of the parasite load in the spleen of Nfat5⁺/⁺ (n = 15) and Nfat5⁻/⁻ (n = 10) infected mice 3 wk after a low-dose inoculation. The horizontal bars represent the mean values for each group in logarithmic scale (Log_{10}). All but one WT animal had parasite burdens below the detection limit of the technique (2.2 parasites/organ). For C, D, and E: three series of independent infections were performed. *, P = 0.01; ***, P < 0.0001, Student’s t test of WT compared with NFAT5-deficient mice.

and their adaptor molecule MyD88 (de Veer et al., 2003; Muraille et al., 2003; Kropf et al., 2004a; Tuon et al., 2008). Production of nitric oxide by iNOS, whose gene is a major target for NFAT5 in the response to TLRs, is a key mechanism for the control and clearance of L. major in vivo (Bogdan et al., 2000; Kropf et al., 2004b) and, in addition, NFAT5⁻/⁻ mice and their WT littermates have a 129/sv background, a resistant strain in which L. major causes a localized infection (Swihart et al., 1995; Lipoldová and Demant, 2006). Mice were infected with a low dose of parasites in the ear or a high dose in the footpad. As expected (Diefenbach et al., 1998), macrophages (F4/80⁺) of WT mice up-regulated iNOS expression at the inoculation site 24 h after infection (Fig. 6 A) which, after a peak at 48 h, decreased to baseline by 72 h with either high or low doses of infection (Fig. 6 B). In contrast, iNOS expression in macrophages from NFAT5-deficient mice was only mildly up-regulated at 48 h after infection (Fig. 6, A and B). Impaired iNOS expression in skin macrophages of NFAT5-deficient mice correlated well with the 5–20-fold higher parasite burden observed in those mice compared with WT ones 72 h after a high-dose infection (Fig. 6 C), and a 20-fold higher parasite burden in the ear and retromaxillar draining lymph nodes 3 wk after a low-dose infection (Fig. 6 D). Notably, although infection was controlled locally and no parasites were detected in the spleen of WT mice, a marked colonization (∼10⁶ parasites/ spleen) was observed in NFAT5-deficient mice (Fig. 6 E). Therefore, our data show that NFAT5 is a key factor in the in vivo response to Leishmania by contributing to iNOS expression in macrophages and control of L. major replication and dissemination.

DISCUSSION

Regulation of gene expression induced by TLRs must integrate variables such as the type of stimulus, the signal strength, and even the repeated encounter with the pathogen they recognize (Foster et al., 2007; Litvak et al., 2009). Current knowledge on transcriptional regulators and mechanisms involved in the induction of specific genes downstream TLRs is still incomplete. In this study, we identify NFAT5 as a key regulator of gene expression in macrophages in response to TLR stimulation and show that it is required for efficient anti-pathogen responses in vivo. Remarkably, this function of NFAT5 is independent of its previously characterized role in the adaptation to hypertonic stress.

Until very recently, NF-κB proteins were the only Rel-like transcription factors known to be involved in innate immune responses activated by receptors that recognize pathogens. This notion was changed by findings describing that
calcineurin-regulated NFATc proteins are activated in innate immune cells by the LPS receptor CD14 or the C-type lectin receptor Dectin-1, although not by TLRs (Goodridge et al., 2007; Zanoni et al., 2009; Greenblatt et al., 2010). Our work now reveals that NFAT5, a distinct Rel-like protein with functional and structural features shared with NF-κB and NFATc proteins, is also a regulator of TLR-induced gene expression. It remains to be addressed whether, like other Rel-domain transcription factors, NFAT5 is involved in responses mediated by other pattern-recognition receptors, such as RIG-like receptors, C-type lectin receptors, and NOD-like receptors (Geijtenbeek and Gringhus, 2009; Takeuchi and Akira, 2010).

NFAT5 controlled the expression of a set of genes involved in different aspects of the response to pathogens. Some of the NFAT5-regulated genes identified here (Tnf and Ccl2) can be also induced by NFAT5 in macrophages under osmotic stress (Roth et al., 2010). However, we found that other genes previously shown to be inducible by osmotic stress in an NFAT5-dependent manner, such as Vegf and Nfkbia (Machnik et al., 2009; Roth et al., 2010), did not require NFAT5 to be expressed in response to LPS. In addition, TLR stimulation did not induce any of the NFAT5-target genes, such as Hspa1b, Akat1b3, and Scl5a, which are characteristically expressed upon osmotic stress in numerous cell types (Aramburu et al., 2006). Although microarray studies of osmoreponsive genes in macrophages have not been reported, it seems likely that NFAT5 might be able to regulate some genes under both types of stimuli: TLR and osmotic stress. Nonetheless, the overlapping would be limited, as osmotic stress and TLRs use different signaling pathways and contexts of transcriptional regulators.

The requirement of NFAT5 for the expression of TLR-regulated genes such as Tnf and Il6, particularly under low stimulus doses, suggests a role for this factor in coupling the strength of signal input to the specificity of gene expression. This property of NFAT5 recalls the requirement for C/EBPβ in Il6 induction during persistent, but not transient, TLR4 responses (Litvak et al., 2009). Therefore, NFAT5 and C/EBPβ represent examples of transcription factors capable of selectively regulating gene expression in the low and high ranges of TLR stimulation. In this regard, NFAT5 could be well suited for fine tuning the expression of its target genes by lowering their inducibility threshold.

The ability of NFAT5 to regulate genes with different transcriptional requirements suggests that it could participate in diverse architectures of transcriptional complexes. In this regard, NFAT5 showed two distinct patterns of association with its target genes: it required TLR activation and de novo protein synthesis to bind a subset of them but was constitutively bound to others regardless of stimulation. Genes to which NFAT5 was bound in basal conditions were primary response, whereas genes to which its binding required TLR stimulation were chromatin remodeling dependent. These observations fit the notion that numerous primary response genes, such as Tnf, are already bound by certain transcription regulators and chromatin remodeling complexes in basal conditions, which likely facilitates their rapid induction upon TLR activation (Ramirez-Carrozzi et al., 2006; Hargreaves et al., 2009). This finding also recalls earlier works describing a constitutive nuclear pool of NFAT5 in different cell types (López-Rodriguez et al., 1999b, 2001) and raises the question of whether this factor might mark a wider set of genes to facilitate their response to diverse stimuli.

The dependence of NFAT5 on de novo protein synthesis for binding to genes such as Nos2 or Il12b did not seem to be a result of new synthesis of NFAT5 itself because its abundance was minimally affected by CHX during the stimulation time used in these experiments (2 h), and it strongly suggests that NFAT5 could require a TLR-induced regulator to be recruited to this group of genes. Binding of NFAT5 to these genes could also be induced without TLR stimulation by inhibiting HDACs with TSA. Although it cannot be ruled out that TSA could act through other mechanisms in addition to inhibiting histone deacetylation, this result suggests that TLR-induced recruitment of NFAT5 to target genes might be primarily controlled by chromatin accessibility. Further analysis showed that recruitment of NFAT5 to Nos2 required IκkBβ, which could potentially act through diverse mechanisms, such as causing posttranslational modifications in NFAT5 or regulatory factors, or inducing, via NF-κB, the de novo expression of a chromatin modifier or a potential NFAT5 partner. Although it remains to be determined whether the need of de novo protein synthesis, sensitivity to HDACs, and regulation by IκkBβ are part of a common mechanism, our combined results suggest that access of NFAT5 to Nos2 and other genes might be controlled by TLR-activated and/or de novo synthesized factors capable of influencing chromatin configurations. Such interpretation is consistent with works showing that TLR-induced chromatin remodelling of genes such as Il12b and Il6 requires de novo protein synthesis (Weinmann et al., 1999; Ramirez-Carrozzi et al., 2006). In addition, TLRs induce the expression of transcriptional regulators and proteins with chromatin remodeling activity, such as C/EBPβ, IκBβ, JMJD3, IκBζ, and IKKe (Yamamoto et al., 2004; De Santa et al., 2007; Kayama et al., 2008; Huang et al., 2009; Litvak et al., 2009; Rao et al., 2010), and TLR-activated NF-κB can de-repress genes such as Nos2 by clearing HDAC complexes (Huang et al., 2009; Glass and Saijo, 2010). The finding that recruitment of NFAT5 to some of its targets depends on protein synthesis also illustrates one mechanism by which de novo protein expression could control the induction of certain secondary response genes.

We found that the NF-κB pathway regulates NFAT5 accumulation downstream of TLRs. As shown recently, the NF-κB pathway can adjust the expression of genes in response to persistent TLR signals by controlling the induction of C/EBPβ (Litvak et al., 2009). The regulation of NFAT5 expression by NF-κB, and its being particularly required for the induction of certain genes, such as Il6, at low doses of stimuli, suggest that NFAT5 could be a relevant component in specific NF-κB–regulated coherent feed-forward loops of
transcriptional circuits involved in sensing low input signals from TLRs (Shoval and Alon, 2010). In addition, the progressive NF-κB–dependent increase of NFAT5 in TLR-stimulated macrophages could be particularly important to sustain the expression of genes with slow induction kinetics, such as Nos2 or Il6.

Finally, our analysis revealed NFAT5 as a key host factor required for controlling infection by L. major, whose clearance strongly depends on TLRs (Tuon et al., 2008) and iNOS production by macrophages (Bogdan et al., 2000; Kropp et al., 2004b). NFAT5-null mice exhibited defective control of the parasite burden at the point of infection and presented colonization of the spleen, resembling the phenotype described for iNOS–deficient mice (Diefenbach et al., 1998), and, indeed, also displayed reduced iNOS expression in local macrophages during L. major infection. The dissemination of the parasite to organs such as the spleen in NFAT5-deficient mice was indicative of visceral leishmaniasis, the most pernicious manifestation of chronic Leishmania infection in humans (Engvandera and Kaye, 2000). These findings underscore the biological relevance of NFAT5 in the response to pathogens, as they show that its deficiency can cause normally resistant 129/sv mice to become highly susceptible to L. major.

MATERIALS AND METHODS

Mice. Mice heterozygous for Nfat5 were described previously (López-Rodríguez et al., 2004). Because NFAT5-null mice in a mixed 129/\(\alpha\)-C57BL/6 background had a severe mortality rate from late embryonic development to early perinatal stages (Go et al., 2004; López-Rodríguez et al., 2004), we bred them for >10 generations to a pure 129/\(\alpha\) background and observed that the rate of survival of NFAT5-null mice (Nfat5\(^{-/-}\)) increased, with >50% of the expected Mendelian ratio of Nfat5\(^{-/-}\) mice reaching adulthood. Nfat5\(^{-/-}\) mice were maintained in an inbred 129/\(\alpha\) background and were crossed to obtain Nfat5\(^{+/+}\) mice and control Nfat5\(^{-/-}\) littermates. Conditional mice that lack IKK\(\beta\) in macrophages, Bb\(^{IKK\beta^{-/-}\text{LyS-m-Cre}}\), were generated crossing Lys-M-Cre mice with Bb\(^{IKK\beta^{-/-}\text{LyS-m-Cre}}\) mice. Lys-M-Cre mice (Claussen et al., 1999) were obtained from The Jackson Laboratory and the Bb\(^{IKK\beta^{-/-}\text{LyS-m-Cre}}\) mice were provided by M. Schmidt-Supprian (Pasparakis et al., 2002). Bb\(^{IKK\beta^{-/-}\text{LyS-m-Cre}}\) and littermate Bb\(^{IKK\beta^{-/-}}\) or Bb\(^{IKK\beta^{+/+}}\) control mice (IKK\(\beta^{-/-}\)) were maintained on a pure C57BL/6 background. All mice were analyzed between 6 and 8 wk of age. Mice were bred and maintained in specific pathogen-free conditions, and animal handling was performed according to institutional guidelines approved by the ethical committee (PRBB/UPF Animal Care and Use Committee).

In vivo infection with Leishmania. For parasite challenge, L. major parasites clone V1 (MHOM/IL/80/Friedlin; provided by M. Soto, Universidad Autónoma de Madrid, Madrid, Spain) were kept in a virulent state by passage in BALB/c mice. The L. major amastigotes were obtained from popliteal lymph nodes of infected BALB/c mice. For transformation from amastigotes to promastigotes, parasites were cultured at 26°C in Schneider's medium (Invitrogen) supplemented with 20% fetal calf serum. Infective-stage promastigotes were isolated from stationary cultures by negative selection using peanut agglutinin (Vector Laboratories; Sacks et al., 1985). Nfat5\(^{-/-}\) or littermate control male mice were infected either by intradermal inoculation of 10\(^6\) metacyclic promastigotes of L. major into the dermis of both ears of each mouse (low dose) or by subcutaneous inoculation in both footpads with 5 \times 10\(^5\) metacyclic promastigotes (high dose). Three series of independent infections were performed. The limiting dilution assay (Bouffet et al., 1995) was used to determine the number of parasites. In brief, homogenized ear and footpad tissue, and mechanically dissociated lymph nodes and spleens, were serially diluted in a 96-well flat-bottomed microtiter plate containing Schneider's medium plus 20% FCS. The number of viable parasites was determined from the highest dilution at which promastigotes could be grown after up to 7 d of incubation at 26°C. In the ear, local draining lymph nodes were excised (retromaxillary and footpad) and spleen, the parasite load is expressed as the number of parasites in the whole organ. In the footpad, the parasite load is expressed as the number of parasites per microgram of tissue. iNOS protein expression was assessed by flow cytometry after intracellular staining, as previously described (Angulo et al., 2000). At the indicated times after L. major infection, footpad sections and ears were recovered from the infected mice as previously described (Iborra et al., 2005). In brief, the ventral and dorsal sheets of the infected ears were separated. The footpad sections and ear sheets were placed in DME containing 50 \(\mu\)g/ml Liberase CI enzyme blend (Roche). After 2 h of incubation at 37°C, the tissues were cut into small pieces, homogenized, and filtered using a cell strainer (70-\(\mu\)m pore size). Cells were first incubated with an antibody to the Fcy receptor (BD) and then stained for surface F4/80 (APC-conjugated antibody to mouse F4/80; eBioscience), fixed, and incubated with a monochlonal antibody to iNOS during permeabilization (Dako). FITC–conjugated iNOS antibody (BD), or the appropriate FITC–conjugated mouse IgG2a isotype control, was used. Events were acquired using a FACSCan flow cytometer (BD) and data were analyzed using FACSDivA (BD) and FlowJo (Tree Star) software.

Reagents. Pam3CSK4 was from Invivogen; zymosan A, polyI:C, LPS from E. coli O55:B5, and loxoborine were from Sigma-Aldrich; CpG DNA was from Hycult Biotechnology; and recombinant mouse IFN-\(\gamma\) was purchased from ImmunoTools. Formaldehyde, sodium chloride, Trizma base, glycine, EDTA, iodoacetamide, sodium pyrophosphate (NaPp), sodium orthovanadate, \(\beta\)-glycerophosphate, PMSF, leupeptin, pepstatin A, aprotinin, SDS, Tween-20, glycine, methanol, Triton X-100 (TX-100), Nonidet P-40, sodium deoxycholate, actinomycin D, dexamethasone, TSA, and CHX were from Sigma-Aldrich. Sodium fluoride (NaF) was from Merck. \(\alpha\)-Amanitin, SB202190, PD98059, SP600125, BAY 11–7082, Nonidet-P-40, sodium deoxycholate, actinomycin D, dexamethasone, TSA, and CHX were from Sigma-Aldrich. Sodium fluoride (NaF) was from Merck. \(\alpha\)-Amanitin, SB202190, PD98059, SP600125, BAY 11–7082, BMS-345541, LY294002, and rnapycin were from EMD.

Isolation of cells and cell culture. Mice RAW 264.7 macrophage cells (American Type Culture Collection) were grown in RPMI 1640 (Invitrogen), supplemented with 10% heat-inactivated fetal bovine serum (HyClone or Invitrogen), 2 mM glutamine (Invitrogen), 50 \(\mu\)M \(\beta\)-mercaptoethanol (Sigma-Aldrich), and 1 mM sodium pyruvate (Invitrogen; complete RPMI medium). To obtain BMDMs, 6–8-wk-old mice were sacrificed and the femoral and tibial marrow was flushed from the bones with DME supplemented with 2 mM glutamine, 50 \(\mu\)M \(\beta\)-mercaptoethanol, and 1 mM sodium pyruvate plus penicillin/streptomycin (Invitrogen; incomplete medium). Cells were then resuspended in complete DMEM (media supplemented with 10% heat-inactivated fetal bovine serum) with 25% (vol/vol) L929-conditioned medium (as the source of macrophage–colony stimulating factor) and incubated for 7 d in polystyrene dishes. Differentiated macrophages were harvested with PBS plus 1 mM EDTA by gentle pipetting, washed with PBS, and plated in tissue culture plates for Western blot, mRNA, and ELISA analysis (2 \times 10\(^5\) cells/3 ml/well). Where indicated, the culture medium was made hypertonic (500 mM OsM/kg) by the addition of 90 mM NaCl from a sterile 4 M stock solution. Osmolality was measured with a vapor pressure osmometer (VAPRO 5520; Wescor).

RAW 264.7 transfection, luciferase assay, and quantification of nitrite levels. RAW 264.7 cells were transfected by electroporation. In brief, 10 \times 10\(^5\) cells in 0.4 ml of ice-cold complete RPMI medium with 20 \(\mu\)g of DNA per cuvette (4-mm gap width; Bogen) were electroporated in a Gene Pulser II (Bio-Rad Laboratories) at 320 V and 975 \(\mu\)F (time constant ranging from 22 to 30 ms). For reporter gene experiments, cells were lysed in passive lysis buffer (PLB; Promega) at 25 \times 10\(^5\) cells/ml and the activity of Firefly and Renilla luciferases was measured with the Dual-luciferase reporter system (Promega) with a Berthold FB12 luminometer (Berthold). Firefly luciferase units were normalized with respect to the activity of Renilla luciferase. The concentration of nitrite produced by RAW 264.7 cells was determined using the Griess assay (Invitrogen) according to manufacturer's indications.
Experiments in RAW 264.7 cells were done with higher doses of TLR ligands than those used in primary macrophages because these were required to induce robust IgA production in the iNOS-luc reporter and, consequently, high doses were also used for the rest of experiments in this cell line.

**Plasmid constructs.** The NFAT5-dependent reporter, ORE-Luc, was previously described (López-Rodríguez et al., 2001), and the iNOS-luc reporter (−1,584 to +161 from the mouse Nos2 gene) was provided by S. Lamas (Centro de Investigaciones Biológicas–Consejo Superior de Investigaciones Científicas, Madrid, Spain). The transfection control plasmid TK-Renilla was from Promega. The GFP-specific shRNA in the pBSU6 vector was previously described (Su et al., 2002) and the two NFAT5-specific shRNAs were done by inserting the following 21-nt sequences complementary to NFAT5 mRNA in pBSU: shNFAT5-1 (shN5-1; Drews-Elger et al., 2009), 5′-GGCTGGCAGCCAGCACTTTTGA-3′, coding sequence common for both human and mouse NFAT5, and shNFAT5-2 (shN5-2), 5′-GGCTGGCAGCGTTCACTACA-3′, coding sequence for mouse NFAT5. Site-directed mutagenesis of the NFAT5 binding site in the iNOS-luc reporter was done using the QuickChange site directed mutagenesis system of Stratagene according to the manufacturer’s instructions and using the following primers: 5′-CACCTTTCTAATGTCAATTCATGGCTATGATGCT-3′ (forward) and 5′-CATGCGCTGAAATTATCTACATGATGCT-3′ (reverse).

**Immunoblot assays.** For protein detection by Western blotting, BMDMs were lysed in TX-100 lysis buffer (0.5–1 × 10^6 cells in 100–200 µl; 1% TX-100, 40 mM Hepes pH 7.4, 120 mM NaCl, 1 mM EDTA, 10 mM NaPiP, 10 mM β-glycerophosphate, 1 mM PMSE, 5 µg/ml leupeptin, 5 µg/ml apro tin, and 1 µg/ml phospho-JNK/SAPK (pT183/pY185) were from BD. Rabbit polyclonal antibody to phospho-p38 (pT180/pY182), to phospho-ERK1/2 (pT202/pY204), monoclonal antibody to IKKα, and mouse monoclonal antibody to α-tubulin were from Santa Cruz Biotechnology, Inc. Mouse monoclonal antibody to L32 was from Imagingex. Mouse monoclonal antibodies to phospho-p38 (pT180/pY182), to phospho-ERK1/2 (pT202/pY204), and to phospho-JNK/SAPK (pT183/pY185) were from BD. Rabbit polyclonal antibody to phospho-MAPKAPK-2 (pT222) was from Cell Signaling Technology. Rabbit polyclonal antibody to IRF3 was from Invitrogen. The antibody to goat IgG coupled to HRP was from Dako, and the antibody to mouse IgG and to rabbit IgG coupled to HRP were from GE Healthcare. Protein bands were visualized by enhanced chemiluminescence, using Supersignal West Pico Chemiluminescent Substrate (Thermo Fisher Scientific).

**Flow cytometry.** 2 × 10^5 cells were blocked for 20 min in 1× PBS containing 10% FBS, 0.1% sodium azide, and 0.2 µg of an antibody to the Fcγ receptor (BD). Cells were then incubated with surface marker-specific antibodies in the same solution (1 µg of antibody for 10^5 cells) and analyzed with a FACScan flow cytometer and CellQuest software (BD). FITC-labeled antibodies to CD11b (BD) or F4/80 (AbD Serotec) were used.

**Measurement of mRNA levels.** Total RNA from BMDMs (2 × 10^6) was isolated using the High Pure RNA Isolation kit (Roche), quantified in a NanoDrop (ND-1000) spectrophotometer, and 1–2 µg of total RNA (50–100 ng for RNA from peritoneal macrophages) was retro-transcribed to cDNA using SuperScript III reverse transcription and random primers (Invitrogen). For real-time quantitative PCR (RT-qPCR), LightCycler 480 SYBR Green I Master (Roche), LightCycler 480 Multiwell Plate (Roche), and the LightCycler 480 Real-Time PCR System (Roche) were used according to the instructions provided by the manufacturers. Samples were normalized to L32 (L32 ribosomal protein gene) mRNA levels using the LightCycler Software, version 1.5. Primer sequences for the PCR reactions are described in Table S2.

**Microarray analysis.** 2 × 10^6 BMDMs left untreated or stimulated for 6 h with 0.3 ng/ml LPS were lysed in 300 µl RLT buffer (RNeasy kit; QIAGEN) and total RNA was isolated using the same system. The RNA integrity was assessed using the Agilent 2100 Bioanalyzer (Agilent Technologies). Labeling and hybridizations were performed according to protocols from Affymetrix. In brief, 100–300 ng of total RNA were amplified and labeled using the WT Sense Target labeling system and control reagents (Affymetrix), and then hybridized to Mouse Gene 1.0 ST Array (Affymetrix). Washing and scanning were performed using the GeneChip System of Affymetrix (GeneChip Hybridization Oven 640, GeneChip Fluidics Station 450, and GeneChip Scanner 7G). Microarray hybridizations were performed for each experimental condition using BMDMs isolated from four independent Nfat5−/− or Nfat5+/+ mice. Microarray data analysis was performed as follows: the robust microarray analysis algorithm was used for background correction (Bolstad et al., 2003; Irizarry et al., 2003a,b), intra- and inter-microarray normalization, and expression signal calculation. Once the absolute expression signal for each gene was calculated in each microarray, the method called significance analysis of microarray (Tusher et al., 2001) was applied to calculate significant differential expression between samples providing p-values adjusted to multiple testing by using false discovery rate (Benjamini and Hochberg, 1995). A false discovery rate cutoff value of 0.1 was used for the differential expression results. All the analysis was done using R and Biocductor packages. The microarray data are available in the Gene Expression Omnibus (GEO) database (http://www.ncbi.nlm.nih.gov/geo) under the accession no. GSE26343.

**ChIP.** BMDMs, grown in 15-cm-diameter polystyrene dishes (20–25 × 10^6 cells) and stimulated with poly I:C or LPS, as indicated in figure legends, were fixed with 0.75% formaldehyde for 10 min at room temperature. Formaldehyde was then quenched with glycine (final concentration 0.26 M) for 5 min. After washing the plates twice with cold PBS, cells were collected with cell scrapers, lysed by 0.75 ml of lysis buffer (50 mM Hepes-KOH pH 7.5, 140 mM NaCl, 1 mM EDTA, 1% TX-100, 0.1% sodium deoxycholate, 0.1% SDS, 1 mM PMSE, 5 µg/ml leupeptin/apro tin, 1 µg/ml pepstatin A, 10 mM NaF, 10 mM sodium orthovanadate, and 10 mM β-glycerophosphate) for 30 min on ice. Lysates were sonicated (Branson 250; Branson Sonic Power) for five cycles of 10 s with constant frequency and intensity 4, to obtain DNA fragments between 300 and 1,000 bp, and centrifuged to remove insoluble debris. Supernatants were collected and 5% of each sample was separated to use as a measure of chromatin input for normalization. The rest of the sample was diluted 10× in dilution buffer (1% TX-100, 20 mM Tris-HCl, pH 8.2, 2 mM EDTA, 150 mM NaCl, 1 mM PMSE, 5 µg/ml leupeptin, 5 µg/ml apro tin, 1 µg/ml pepstatin A, 10 mM NaF, 10 mM sodium orthovanadate, and 10 mM β-glycerophosphate) for immunoprecipitation. Samples were precleared with protein A Sepharose beads (GE Healthcare) that were previously pre-adsorbed with fish sperm DNA (Roche) and bovine serum albumin (New England Biolabs) for 1 h at 4°C. Specific antibodies were added after removing the pre-cleaning beads. To immunoprecipitate Nfat5, a mixture of two rabbit polyclonal antibodies to NFAT5 specific for its amino-terminal or DNA binding domain regions (López-Rodríguez et al., 1999b) was used, and preimmune serum served as control. To immunoprecipitate Nfat−κB, 390
an antibody to p65 (Santa Cruz Biotechnology, Inc.) was used and normal rabbit IgG (Santa Cruz Biotechnology, Inc.) was included as a control. Antibodies were then added to the blots and incubated overnight at 4°C. Pre-adSORbed protein A Sepharose beads were then added, incubated for 1 h at 4°C, and then washed three times with washing buffer (0.1% SDS, 1% TX-100, 20 mM Tris-HCl pH 8, 2 mM EDTA, and 150 mM NaCl) and once with final washing buffer (0.1% SDS, 1% TX-100, 20 mM Tris-HCl pH 8, 2 mM EDTA, and 500 mM NaCl). To elute the DNA, beads were incubated with elution buffer (1% SDS and 100 mM NaHCO₃) for 15 min at room temperature. To reverse the cross-linking, samples were incubated overnight at 65°C with 6 ng/μl RNase (Roche) and DNA was purified using the QIAGEN PCR purification system. DNA was then subjected to RT-qPCR using the primers described in Table S2. Immunoprecipitated DNA from each sample was normalized to its respective chromatin input.

**Cytokine production.** Supernatants from the same cultures (2 x 10⁶ cells in 3 ml of media) from which RNA was processed were harvested and TNF and IL-6 were measured by ELISA (R&D Systems) with an Opsys MR plate reader (Dynex Technologies).

**Statistical analysis.** Statistical significance of the experimental data were determined by the paired Student’s t test.

**Online supplemental material.** Fig. S1 shows the induction of a group of poly IC–induced genes in NFAT5–deficient macrophages, and also shows the effect of NFAT5 in the expression of iNOS/Nos2 in macrophages stimulated with the combination of LPS plus IFN-γ. Fig. S2 shows that macrophages isolated from the BM of NFAT5–deficient mice differentiate normally and display normal activation of the major signaling pathways downstream TLRs. Fig. S3 shows that in vitro differentiation and TLR–mediated activation of macrophages do not cause an osmotic stress response. Fig. S4 illustrates the potential binding sites for NFAT5 in various target genes, and shows its association with a group of targets upon poly IC stimulation of macrophages. Fig. S5 displays controls for the effect of IKKβ deletion in macrophages, and also shows the expression of Tnf and Nos2 in response to LPS in NFAT5–deficient macrophages pretreated with CHX. Table S1 lists genes that are differentially expressed between LPS-treated control and LPS in NFAT5-deficient macrophages pretreated with CHX. Table S2 includes a list of the primers used in this study. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.201111569/DC1.

We greatly acknowledge Drs. Andrea Ceruti, Angel Corbi, and Miguel López-Botet for insightful comments and critical reading of the manuscript. The authors thank Drs. Carlos Ardavin, Lisardo Boscá, Antonio Celada, Santiago Lamas, Pura Muñoz-Cánoves, and Manuel Soto for reagents, and Dr. Marc Schmidt-Supprian for IKKβ floxed mice. We also thank Drs. Encarna Fermiñán, Diego Alonso, and Lara Nonell for assistance with mouse genotyping and technical assistance with mouse genotyping.

C. López-Rodríguez was supported by the Ramón y Cajal and I3 Researchers Programmes and grants from the Spanish Government (SAF2006-04913 and SAF2009-08066) and European Union (MCRES16308). J. Aramburu was supported by grants from the Spanish Government (BFU2008-01070 and SAF2011-24268), and Distinción de la Generalitat de Catalunya per a la Promoció de la Recerca Universitària. Research in the laboratories of C. López-Rodríguez and J. Aramburu is also supported by Fundació la Marató TV3 (030230/31, 080730), Spanish Ministry of Health (ISCIII-RETIC RD06/0009-FEDER), and Generalitat de Catalunya (2009 SGR 601). M. Buadax was supported by a Beatrix de Piñós postdoctoral contract from Generalitat de Catalunya. S. Iborra was supported by a Sara Borrell postdoctoral contract from the Ministry of Health of Spain. J. Minguiñol and R. Berga-Bolaños were supported by predoctoral fellowships from the Spanish Government.

The authors have no conflicting financial interests.

Author contributions: M. Buadax, G. Lunazzi and J. Minguiñol performed and analyzed most of the experiments; S. Iborra and M. del Val designed, did, and analyzed the L major experiments; R. Berga-Bolaños did and analyzed the reporter assays; J. Aramburu provided critical advice and interpreted the data; and C. López-Rodríguez designed the study, interpreted the data, and wrote the manuscript.

**Submitted: 28 July 2011 Accepted: 3 January 2012**

**REFERENCES**

Angulo, I., F.G. de las Heras, J.F. García-Bustos, D. Gargallo, M.A. Muñoz-Fernández, and M. Fresno. 2000. Nitric oxide-producing CD11b(+)/Ly-6G(Gr-1)+CD31(ER-MP12)(+) cells in the spleen of cyclophosphamide-treated mice: implications for T-cell responses in immunosuppressed mice. Blood. 95:212–220.

Aramburu, J., K. Drews-Elger, A. Estrada-Gelonch, J. Minguiñol, B. Morachon, V. Santiago, and C. López-Rodríguez. 2006. Regulation of the hypertonic stress response and other cellular functions by the Rel-like transcription factor NFAT5. *Biochem. Pharmacol.* 72:1597–1604. http://dx.doi.org/10.1016/j.bcp.2006.07.002

Benjamini, Y., and Y. Hochberg. 1995. Controlling the false discovery rate: A practical and powerful approach to multiple testing. *J. R. Stat. Soc. Series B Stat. Methodol.* 57:289–300.

Berga-Bolaños, R., K. Drews-Elger, J. Aramburu, and C. López-Rodríguez. 2010. NFAT5 regulates T lymphocyte homeostasis and CD24-dependent T cell expansion under pathologic hypernatremia. *J. Immunol.* 185:6624–6635. http://dx.doi.org/10.1186/1471-2415-10-368

Bogdán, C., M. Rollönhoff, and A. Diefenbach. 2000. The role of nitric oxide in innate immunity. *Immunol. Rev.* 173:17–26. http://dx.doi.org/10.1034/j.1600-065X.2000.91730.x

Bolstad, B.M., R.A. Irizarry, M. Astrand, and T.P. Speed. 2003. A comparison of normalization methods for high density oligonucleotide array data based on variance and bias. *Bioinformatics.* 19:185–193. http://dx.doi.org/10.1093/bioinformatics/19.2.185

Buffet, P.A., A. Sulahian, Y.J. Garin, N. Nassar, and F. Derouin. 1995. Culture microtirrotation: a sensitive method for quantifying Leishmania infantum in tissues of infected mice. *Antimicrob. Agents Chemother.* 39:2167–2168.

Caivano, M., B. Gorgoni, P. Cohen, and V. Poli. 2001. The induction of cyclooxygenase-2 mRNA in macrophages is biphasic and requires both CCAAT enhancer-binding protein beta (C/EBPbeta) and C/EBP delta transcription factors. *J. Biol. Chem.* 276:48693–48701. http://dx.doi.org/10.1074/jbc.M108222200

Clausen, B.E., C. Burkhardt, W. Reith, R. Renkawitz, and I. Förster. 1999. Conditional gene targeting in macrophages and granulocytes using LysM+ mice. *Transgenic Res.* 8:265–277. http://dx.doi.org/10.1023/A:1008942828960

De Santa, F., M.G. Totaro, E. Prosperini, S. Notarbartolo, G. Testa, and G. Natale. 2007. The histone H3 lysine-27 dimethylated H3Lys3 links inflammation to inhibition of polycomb-mediated gene silencing. *Cell.* 130:1083–1094. http://dx.doi.org/10.1016/j.cell.2007.08.019

De Vries, M.J., J.M. Curtis, T.M. Baldwin, C. Tudor-Dobosco, A. Sexton, M.J. McConvill, E. Handman, and L. Schofield. 2003. MyD88 is essential for clearance of Leishmania major: possible role for lipophosphoglycan and Toll-like receptor 2 signaling. *Eur. J. Immunol.* 33:2822–2831. http://dx.doi.org/10.1002/eji.200324128

Diefenbach, A., H. Schindler, N. Donhausser, E. Lorenz, T. Laskay, J. MacMicking, M. Rollönhoff, I. Greser, and C. Bogdán. 1998. Type 1 interferon (IFNα/β) and type 2 nitric oxide synthase regulate the innate immune response to a protozoan parasite. *Immunity.* 8:77–87. http://dx.doi.org/10.1016/S1074-7613(00)80460-4

Dong, C., R.J. Dave, and R.A. Flavell. 2002. MAP kinases in the immune response. *Annu. Rev. Immunol.* 20:55–72. http://dx.doi.org/10.1146/annurev.immunol.20.093001.160701

Drews-Elger, K., M.C. Ortel, A. Rao, C. López-Rodríguez, and J. Aramburu. 2009. The transcription factor NFAT5 is required for cyclophosphamide effect and cell cycle progression in cells exposed to hypertonic stress. *PLoS ONE.* 4:e5245. http://dx.doi.org/10.1371/journal.pone.00005245

Engveld, C.R., and P.M. Kaye. 2000. Organ-specific immune responses associated with infectious disease. *Immunol. Today.* 21:73–78. http://dx.doi.org/10.1016/S1074-7613(00)01549-2

Foster, S.L., D.C. Hargreaves, and R. Medzhitov. 2007. Gene-specific control of inflammation by TLR-induced chromatin modifications. *Nature.* 447:972–978.
Kino, T., H. Takatori, I. Manoli, Y. Wang, A. Tsulpakov, M.R. Blackman, Y.A. Su, G.P. Chrousos, A.H. DeCherney, and J.H. Segars. 2009. Bex mediates the response of lymphocytes to osmotic stress through the activation of NFAT5. Sci. Signal. 2:ra5. http://dx.doi.org/10.1126/scisignal.2000881

Ko, B.C., A.K. Lam, A. Kapus, L. Fan, S.K. Chung, and S.S. Chung. 2002. Fyn and p38 signaling are both required for maximal hypertonic activation of the osmotic response element-binding protein/tonicity-responsive enhancer-binding protein (OREBP/TonEBP). J. Biol. Chem. 277:46085–46092. http://dx.doi.org/10.1074/jbc.M208138200

Kropf, P., M.A. Freundenberg, M. Modolell, H.P. Price, S. Herath, S. Antoniuzzi, C. Galanos, D.F. Smith, and I. Müller. 2004a. Toll-like receptor 4 contributes to efficient control of infection with the protozoan parasite Leishmania major. Infect. Immun. 72:1920–1928. http://dx.doi.org/10.1128/IAI.72.4.1920-1928.2004

Kropf, P., N. Freundenberg, C. Kalis, M. Modolell, S. Herath, C. Galanos, M. Freundenberg, and I. Müller. 2004b. Infection of C57BL/10ScCr and C57BL/10SnCrl mice with Leishmania major reveals a role for Toll-like receptor 4 in the control of parasite replication. J. Leukoc. Biol. 76:48–57. http://dx.doi.org/10.1128/JLB.0703484

Lam, C.A., F. Yao, J.J. Wong, J. George, H. Xu, K.P. Chu, W.K. Sung, L. Lipovich, V.B. Vega, J. Chen, et al. 2007. Genome-wide mapping of RELA(65) binding identifies E2F1 as a transcriptional activator recruited by NF-kappaB upon TLR4 activation. Mol. Cell. 27:622–635. http://dx.doi.org/10.1016/j.molcel.2007.06.038

Lipoldová, M., and P. Demant. 2006. Genetic susceptibility to infectious disease: lessons from mouse models of leishmaniasis. Nat. Rev. Genet. 7:294–305. http://dx.doi.org/10.1038/nrg1832

Litvak, V., S.A. Ramsey, A.G. Rust, D.E. Zak, K.A. Kennedy, A.E. Lampano, M. Nyktor, I. Shumylevich, and A. Adedram. 2009. Function of C/EBPbeta in a regulatory circuit that discriminates between transient and persistent TLR-4-induced signals. Nat. Immunol. 10:437–443. http://dx.doi.org/10.1038/ni.1721

Liu, Y., Y. Wang, M. Yamakuchi, S. Isowaki, E. Nagata, Y. Kanamura, I. Kitajima, and I. Maruyama. 2001. Upregulation of toll-like receptor 2 gene expression in macrophage response to peptidoglycan and high concentration of lipopolysaccharide is involved in NF-kappaB activation. Infect. Immun. 69:2788–2796. http://dx.doi.org/10.1128/IAI.69.5.2788-2796.2001

López-Rodríguez, C., J. Aramburu, A.S. Rakeman, N.G. Copeland, D.J. Gilbert, S. Thomas, C. Disteche, N.A. Jenkins, and A. Rao. 1999a. NFAT5: the NF-AT family of transcription factors expands in a new direction. Cold Spring Harb. Symp. Quant. Biol. 64:517–526. http://dx.doi.org/10.1101/sqb.1999.64.517

López-Rodríguez, C., J. Aramburu, A.S. Rakeman, and A. Rao. 2001. Bridging the NFAT and NF-kappaB families: NFAT5 dimerization regulates cytokine gene transcription in response to osmotic stress. Immunity. 15:47–58. http://dx.doi.org/10.1016/S1074-7613(01)00165-0

López-Rodríguez, C., C.L. Antos, J.M. Shelton, J.A. Richardson, F. Lin, T.I. Novobrantseva, R.T. Bronson, P. Igarashi, A. Rao, and E.N. Olson. 2004. Loss of NFAT5 results in renal atrophy and lack of tonicity-responsive gene expression. Proc. Natl. Acad. Sci. USA. 101:2392–2397. http://dx.doi.org/10.1073/pnas.0307203100

Machnik, A., W. Neuhofer, J. Jantich, A. Dahlmann, T. Tammela, K. Machura, J.K. Park, F.X. Beck, D.N. Müller, W. Derer, et al. 2009. Macrophages regulate salt-dependent volume and blood pressure by a vascular endothelial growth factor C-dependent buffering mechanism. Nat. Med. 15:545–552. http://dx.doi.org/10.1038/nm.1960

Medzhitov, R., and T. Honig. 2009. Transcriptional control of the inflammatory response. Nat. Rev. Immunol. 9:692–703. http://dx.doi.org/10.1038/nri2634

Meylan, E., J. Tschopp, and M. Karin. 2006. Intracellular pattern recognition receptors in the host response. Nature. 442:39–44. http://dx.doi.org/10.1038/nature04946

 Miyakawa, H., S.K. Woo, S.C. Dahl, J.S. Handler, and H.M. Kwon. 1999. Tonicity-responsive enhancer binding protein, a rel-like protein that
stimulates transcription in response to hypertonicity. *Proc. Natl. Acad. Sci. USA* **96**:2538–2542. http://dx.doi.org/10.1073/pnas.96.5.2538

Morano, B., J. Mingualón, J.D. Molkentin, C. López-Rodríguez, and J. Aramburu. 2008. Analysis of the transcriptional activity of endogenous NFAT5 in primary cells using transgenic NFAT-luciferase reporter mice. *BMC Mol. Biol.* 9:13. http://dx.doi.org/10.1186/1471-2199-9-13

Muraille, E., C. De Trefz, M. Braut, P. De Baetselier, O. Leo, and Y. Carboni. 2003. Genetically resistant mice lacking MyD88-adaptor protein display a high susceptibility to Leishmania major infection associated with a polarized Th2 response. *J. Immunol.* 170:4237–4241.

O’Neill, L.A., and A.G. Bowie. 2007. The family of five: TIR-domain-containing adaptors in Toll-like receptor signalling. *Nat. Rev. Immunol.* 7:353–364. http://dx.doi.org/10.1038/nri2079

Ogawa, S., J. Lozach, K. Jepsen, D. Sawka-Verhelle, V. Perissi, R. Sasaki, D.W. Rose, R.S. Johnson, M.G. Rosenfeld, and C.K. Glass. 2004. A nuclear receptor corepressor transcriptional checkpoint controlling activator protein 1-dependent gene networks required for macrophage activation. *Proc. Natl. Acad. Sci. USA* **101**:14461–14466. http://dx.doi.org/10.1073/pnas.0408761101

Pascual, G., A.L. Fong, S. Ogawa, A. Gambiel, A.C. Li, V. Persoiu, D.W. Rose, T.M. Wilson, M.G. Rosenfeld, and C.K. Glass. 2005. A SUMOylation-dependent pathway mediates trans repression of inflammatory response genes by PPAR-gamma. *Nature* **437**:759–763. http://dx.doi.org/10.1038/nature03988

Paparakis, M., G. Courtois, M. Hafner, M. Schmidt-Suppkan, A. Nenci, A. Toksoy, M. Krapfett, M. Goeberler, R. Gilillter, A. Israel, et al. 2002. TNF-mediated inflammatory skin disease in mice with epidermis-specific deletion of IKK2. *Nature* **417**:861–866. http://dx.doi.org/10.1038/ulike00560

Ramirez-Carrozzi, V.R., A.A. Nazarian, C.C. Li, S.L. Gore, R. Sridharan, A.N. Imbalzano, and S.T. Smale. 2006. Selective and antagonistic functions of SWI/SNF and Mi-2beta nucleosome remodeling complexes during an inflammatory response. *Genes Dev.* **20**:282–296. http://dx.doi.org/10.1101/gad.1383206

Ramirez-Carrozzi, V.R., D. Bras, D.M. Bhatt, C.S. Cheng, C. Hong, K.R. Doty, J.C. Black, A. Hoffmann, M. Carey, and S.T. Smale. 2009. A unifying model for the selective regulation of inducible transcription by CpG islands and nucleosome remodeling. *Cell* **138**:114–128. http://dx.doi.org/10.1016/j.cell.2009.04.020

Rao, A., C. Luo, and P.G. Hogan. 1997. Transcription factors of the NFAT family: regulation and function. *Annu. Rev. Immunol.* **15**:707–747. http://dx.doi.org/10.1146/annurev.immunol.15.1.707

Rao, P., M.S. Hayden, M. Long, M.L. Scott, A.P. West, D. Zhang, A. Oeckinghaus, C. Lynch, A. Hoffmann, D. Balmore, and S. Ghosh. 2010. IkkappaBbeta acts to inhibit and activate gene expression during the inflammatory response. *Nature* **466**:1115–1119. http://dx.doi.org/10.1038/nature09283

Roth, L., V. Leroy, H.M. Kwon, P.Y. Martin, E. Féralle, and U. Haeber. 2010. Osmoprotective transcription factor NFAT5/TonEBP modulates nuclear factor-kappaB activity. *Mol. Biol. Cell* **21**:3459–3474. http://dx.doi.org/10.1091/mbc.E10-02-0133

Saccani, S., S. Pantano, and G. Natoli. 2001. Two waves of nuclear factor-kB recruitment to target promoters. *J. Exp. Med.* 193:1351–1359. http://dx.doi.org/10.1084/jem.193.12.1351

Sacks, D.L., S. Henry, and A. Sher. 1985. Identification of cell surface carbohydrate and antigenic changes between noninfective and infective developmental stages of *Leishmania major* promastigotes. *J. Immunol.* **135**:564–569.

Shoval, O., and U. Alon. 2010. SnapShot: network motifs. *Cell* 143:326–e1. http://dx.doi.org/10.1016/j.cell.2010.09.050

Stroud, J.C., C. López-Rodríguez, A. Rao, and L. Chen. 2002. Structure of a TonEBP-DNA complex reveals DNA encircled by a transcription factor. *Nat. Struct. Biol.* **9**:90–94. http://dx.doi.org/10.1038/nsb749

Sui, G., C. Sooshoo, B. Affar, F. Gay, Y. Shi, W.C. Forrester, and Y. Shi. 2002. A DNA vector-based RNAi technology to suppress gene expression in mammalian cells. *Proc. Natl. Acad. Sci. USA* **99**:5515–5520. http://dx.doi.org/10.1073/pnas.082117599

Swilhart, K., U. Fruth, N. Messner, K. Hug, R. Behn, S. Huang, G. Del Giudice, M. Agu et, and J.A. Louis. 1995. Mice from a genetically resistant background lacking the interferon-γ receptor are susceptible to infection with *Leishmania major* but mount a polarized TH helper cell type 1 CD4+ T cell response. *J. Exp. Med.* 181:961–971. http://dx.doi.org/10.1084/jem.181.3.961

Takeuchi, O., and S. Akira. 2010. Pattern recognition receptors and inflammation. *Cell* **140**:805–820. http://dx.doi.org/10.1016/j.cell.2010.01.022

Tuon, F.F., V.S. Amato, H.A. Bacha, T. Almusawi, M.I. Duarte, and V. Amato Neto. 2008. Toll-like receptors and leishmaniasis. *Infect. Immun.* **76**:866–872. http://dx.doi.org/10.1128/IAI.01090-07

Tusher, V.G., R. Tibshirani, and G. Chu. 2001. Significance analysis of microarrays applied to the ionizing radiation response. *Proc. Natl. Acad. Sci. USA* **98**:5116–5121. http://dx.doi.org/10.1073/pnas.091062498

Wienmann, A.S., S.E. Plevy, and S.T. Smale. 1999. Rapid and selective remodeling of a positioned nucleosome during the induction of IL-12 p40 transcription. *Immunity* **11**:665–675. http://dx.doi.org/10.1016/S1074-7613(00)80141-7

West, A.P., A.A. Kobalnsky, and S. Ghosh. 2006. Recognition and signaling by toll-like receptors. *Annu. Rev. Cell Dev. Biol.* **22**:409–437. http://dx.doi.org/10.1146/annurev.cellbio.21.122303.115827

Wietek, C., S.M. Miggin, C.A. Jefferies, and L.A.J. O’Neill. 2003. Interferon regulatory factor-3-mediated activation of the interferon-sensitive response element by Toll-like receptor (TLR) 4 but not TLR3 requires the p65 subunit of NF-κB. *J. Biol. Chem.* **278**:50923–50931. http://dx.doi.org/10.1074/jbc.M30813520

Xie, Q.W., R. Whisnant, and C. Nathan. 1993. Promoter of the mouse gene encoding calcium-independent nitrile oxide synthase confers inducibility by interferon gamma and bacterial lipopolysaccharide. *J. Exp. Med.* **177**:1779–1784. http://dx.doi.org/10.1084/jem.177.6.1779

Yamamoto, M., S. Yamazaki, S. Uematsu, S. Sato, H. Hemmi, K. Hoshino, T. Kaisho, H. Kuwata, O. Takeuchi, K. Takeshige, et al. 2004. Regulation of Toll/IL-1-receptor-mediated gene expression by the inducible nuclear protein IkkappaBzeta. *Nature* **430**:218–222. http://dx.doi.org/10.1038/nature01278

Zanoni, I., R. Ostuni, G. Capuano, M. Collini, M. Caccia, A.E. Ronchi, M. Rocchetti, F. Mingozzi, M. Fotti, G. Chirico, et al. 2009. CD14 regulates the dendritic cell life cycle after LPS exposure through NFAT activation. *Nature* **460**:264–268. http://dx.doi.org/10.1038/nature08118