Mast Cell TLR2 Signaling Is Crucial for Effective Killing of Francisella tularensis


J Immunol published online 23 April 2012
http://www.jimmunol.org/content/early/2012/04/23/jimmunol.1200039

Supplementary Material
http://www.jimmunol.org/content/suppl/2012/04/24/jimmunol.1200039.DC1

Subscription
Information about subscribing to The Journal of Immunology is online at:
http://jimmunol.org/subscription

Permissions
Submit copyright permission requests at:
http://www.aai.org/About/Publications/JI/copyright.html

Email Alerts
Receive free email-alerts when new articles cite this article. Sign up at:
http://jimmunol.org/alerts
Mast Cell TLR2 Signaling Is Crucial for Effective Killing of *Francisella tularensis*

Annette R. Rodriguez,*† Jieh-Juen Yu,* M. Neal Guentzel,* Christopher S. Navara,* Karl E. Klose,* Thomas G. Forsthuber,* James P. Chambers,* Michael T. Berton,‡ and Bernard P. Arulanandam*  

TLR signaling is critical for early host defense against pathogens, but the contributions of mast cell TLR-mediated mechanisms and subsequent effector functions during pulmonary infection are largely unknown. We have previously demonstrated that mast cells, through the production of IL-4, effectively control *Francisella tularensis* replication. In this study, the highly human virulent strain of *F. tularensis* SCHU S4 and the live vaccine strain were used to investigate the contribution of mast cell/TLR regulation of *Francisella*. Mast cells required TLR2 for effective bacterial killing, regulation of the hydrolytic enzyme cathepsin L, and for coordination and trafficking of MHC class II and lysosomal-associated membrane protein 2. Infected TLR2−/− mast cells, in contrast to wild-type and TLR4−/− cells, lacked detectable IL-4 and displayed increased cell death with a 2–3 log increase of *F. tularensis* replication, but could be rescued with rIL-4 treatment. Importantly, MHC class II and lysosomal-associated membrane protein 2 localization with labeled *F. tularensis* in the lungs was greater in wild-type than in TLR2−/− mice. These results provide evidence for the important effector contribution of mast cells and TLR2-mediated signaling on early innate processes in the lung following pulmonary *F. tularensis* infection and provide additional insight into possible mechanisms by which intracellular pathogens modulate respiratory immune defenses. *The Journal of Immunology*, 2012, 188: 000–000.

Mast cells act as sentinels that sense bacterial products via host surface pattern recognition receptors such as TLR2 and TLR4 (1, 2). Although mast cell cytokine production following TLR recognition has been well documented (3–7), much is still unknown about mast cell TLR signaling and function during bacterial infection. In dendritic cells, TLR signaling triggers bacterial phagocytosis and promotes phagosome maturation, which entails nascent phagosome fusion with endosomes and phagolysosomal formation (8). Phagocytosis, phagosome maturation (9), and phagosome movement along microtubules to perinuclear regions require optimal pH regulation (10, 11). Although the maturation process has been studied in dendritic cells (8, 12, 13), the contribution of TLR function in mast cell phagocytosis is yet to be elucidated.

Phagosome maturation in myeloid lineage cells is marked by protein accumulation, including CD63 (14), lysosomal-associated membrane protein (LAMP)1/2 (15), and Rab7 (16, 17). Additional proteins in this process include the V-type ATPase, MHC class II (MHCII), and lysosomal hydrolases. To this end, lysosomal hydrolases are comprised of several cathepsins such as serine, aspartate, and cysteine proteases (18–20). Among the cathepsins, cathepsin L is critical for cellular homeostasis, autophagy, apoptosis, and Ag processing and presentation (21, 22). Importantly, this protease also has been implicated in various diseases, including diabetes (23), cancer (24), and lung inflammation (25), and therefore must be expediently regulated to maintain homeostasis.

Under ideal conditions, phagosome/lysosome fusion leads to a decrease in pH and protease activation, which culminates in killing of pathogens within the phagolysosome. However, a number of pathogens have developed evasion mechanisms by modifying the phagosome or maturation events. For example, *Mycobacterium* spp. block the Rab5-positive stage (26), *Leishmania* spp. inhibit phagosome maturation (27), and *Coxiella burnetii* converts the phagosome into a hybrid autophagosome (28). *Francisella tularensis*, the causative agent of pneumonic tularemia, has been shown to escape the phagosome to evade lysosomal degradation and undergoes extensive replicaion within the macrophage cytosol (29).

TLR2 signaling and ensuing immune responses are important for the control of pulmonary *F. tularensis* (30). Whereas TLR2 has been shown to be involved in recognition of *Francisella* lipoproteins (30–32), wild-type (WT), TLR2−/−, and TLR4−/− macrophages have been shown to exhibit similar susceptibility to *F. tularensis* infection. We have recently shown that mast cells are essential for host survival during pulmonary *F. tularensis* challenge, and that mast cells cocultured with macrophages promote killing of the organism via IL-4 secretion (33) and increased macrophage cellular ATP production with subsequent acidification (34).

Although cellular acidic conditions have been shown to control trafficking along microtubules (10, 35), and Yates and Russell (36) have shown that macrophage TLR2/4 signaling is not required for phagosome maturation, there is a paucity of information on mast
cell TLR function and control of cellular trafficking and lysosomal function. Accordingly, using the highly human virulent strain of *F. tularensis* (SCHU S4) and *F. tularensis* live vaccine strain (LVS), we investigated the contribution of mast cell TLR2/4 and IL-4 production to killing by mast cells. Our findings show that mast cell TLR2 is critical for optimal trafficking of cellular proteins and effective host responses during *Francisella* infection.

**Materials and Methods**

**Mice**

Specific pathogen-free 4- to 8-week-old mice were used for all procedures. C57BL/6 mice were purchased from the National Cancer Institute. TLR2−/− and TLR4−/− mice were provided by Dr. M.T. Burton. All experimental procedures and animal care were performed in accordance with the Institutional Animal Care and Use Committee guidelines.

**Bacteria**

*F. tularensis* LVS (obtained from Dr. R. Lyons at the University of New Mexico), *F. tularensis* SCHU S4 (obtained from the Centers for Disease Control), and mCherry LVS (KKF314) were grown in tryptic soy broth supplemented with L-cysteine (33). Experiments using SCHU S4 were conducted in a licensed animal biosafety level 3 facility.

**Generation of primary cells and in vitro infection**

Mast cells were derived from mouse bone marrow and infected in vitro as described previously (33). Briefly, cells were counted, plated, and incubated for 1 h at 37 °C and analyzed at various times. At 3, 12, or 24 h postchallenge with LVS (multiplicity of infection [MOI] 100) or *F. tularensis* SCHU S4 (MOI 100), bacteria were dilution plate counted using cellular lysates. In separate experiments, murine rIL-4 (5 or 25 ng/ml; eBioscience) was added to cell cultures 2 h prior to infection and rIL-4 was replaced after each wash step. Cells were used for determination of bacterial replication and protein expression.

**In vivo challenge and flow cytometry**

Six- to 8-week-old C57BL/6 and TLR2−/− mice were challenged intranasally with either 1 or 10 LD₅₀ LVS or with PBS (mock challenge). At days 2 and 4 postchallenge, mice were euthanized. The lungs were perfused with 1× PBS and stained with a 70-μm cell strainer, or formalin was injected into the trachea and the lungs were fixed in neutral formalin overnight, dehydrated, and embedded in paraffin. Serial sections of 5 μm thickness were prepared. Tissue sections were permeabilized with 1× Perm/Wash buffer and blocked with BSA or rat serum. Tissues were stained for 45 min at room temperature with fluorochrome-conjugated Abs, including anti–CD117, anti-LAMP2, anti-CD49b, anti-CD11c, or anti-F480 (BD Biosciences), and DAPI. Lung cells were washed with 2% FBS in 1× PBS with 0.09% sodium azide (PBS wash), then blocked with 10% rat serum in 1× PBS at 4 °C for 30 min. Samples were washed and surfaced stained with appropriate fluorochrome-conjugated Ab or isotype control, incubated at 4 °C for 30 min, and washed. Samples were then fixed in Cytotox/Cytoperm for 20 min, washed with PBS, and treated with 1× Perm/Wash for 10 min, and the wash was removed. Cells were then stained with fluorochrome-conjugated Ab or isotype control diluted in 100 μl 1× Perm/Wash and added to appropriate samples. Samples were then incubated for 60 min with intermittent agitation, washed in 1× Perm/Wash, and resuspended in 2% (v/v) paraformaldehyde for flow cytometric analysis (FACSCalibur; BD Biosciences). Analyses were performed using CellQuest Pro software (BD Biosciences). Lung tissues also were examined using a 510 Meta confocal microscope (Zeiss), and data were analyzed using Imaris software (Bitplane, St. Paul, MN).

For in vitro analysis of mast cells and cocultures, cells were collected at 15, 30, and 60 min, 3, 12, or 24 h and washed with PBS. Samples were subsequently blocked with anti-mouse CD16/CD32 (BD Biosciences) or with 10% rat serum at 4 °C, followed by addition of fluorescent-conjugated Abs for surface and/or intracellular staining as noted above. Fluorescent Abs included FcRL (PE), c-Kit FITC (clone 2B8; eBioscience), CD11b (FITC or allophycocyanin), CD206 (clone MR5D3; BioLegend), or isotype controls (IgG1–PE, IgG2a–FITC, IgG2a–allophycocyanin, IgG2a–Alexa 488). For indirect staining of cathepsin L, secondary Ab with fluorochrome-conjugated Alexa 488 or Texas Red was used. Gating for analyses included side scatter versus c-Kit for primary mast cells, or CD11b for macrophages. Analyses of data were performed using CellQuest Pro software.

**Microscopy**

Lucifer yellow-labeled bacteria were used for in vitro infection as described above; however, mast cells were cultured in polystyrene tubes or with 10% RPMI 1640 containing 0.1% gelatin (stabilization for tracking) in a 35-mm dish (Ibidi, Munich, Germany) for live imaging. For analysis of acidification (39), a specific acidification probe (Lysotracker Red DND-99; Invitrogen, Eugene, OR) was added to cultures and incubated for 30 min at 37 °C prior to infection. Lucifer yellow-labeled LVS was added and cells were collected and stained at designated intervals as previously described for surface staining, followed by fixing, permeabilization, and intracellular staining for 2 h at room temperature. A CytoPro was used at 800 rpm for 4 min to collect the cells on poly-l-lysine–coated slides. Permount was added to the slides, coverslips were placed, and slides were dried overnight at room temperature in the dark. Samples were examined using a confocal microscope (Zeiss 510 Meta; Carl Zeiss Microimaging, Thornwood, NY) and analyzed with Imaris software. For live cell imaging of WT and TLR2−/− mast cells, the personal DeltaVision fluorescent deconvolution microscope was used with either a ×60 or 100 high numerical aperture objective. During acquisition of images, cells were maintained at 37 °C with 5% CO₂ with acquisition of images at 60-s intervals.

Confocal microscopy was employed for lung tissue analysis using a Zeiss LSM 510 confocal microscope. Lasers and settings for detection of fluorophores included: 405 for detection of DAPI (BP 420–480), 488 for detection of Alexa 488 (NFT 490 and BP 505–530), 594 for detection of mCherry (NFT 545 and BP 560–615), and 633 for detection of allophycocyanin (NFT 545 and LP 650).

**Statistics**

Data were analyzed by a Student *t* test using the statistical software program SigmaStat (Systat Software, Chicago, IL). A *p* value ≤ 0.05 was considered statistically significant. Results are representative of at least two independent experiments.

**Results**

**WT and TLR4−/− mast cells effectively control Francisella replication, whereas TLR2−/− mast cells are permissive to Francisella replication**

TLR2-deficient (TLR2−/−) mice have been shown to exhibit higher mortality than do WT mice following *F. tularensis* pulmonary challenge (30, 32). Given that WT, TLR2−/−, and TLR4−/− macrophages exhibit similar susceptibility to *Francisella*, and that we have previously shown that mast cells are important for bacterial control and survival during pulmonary *F. tularensis* infection (33), we compared replication in WT and TLR-deficient mast cells during *Francisella* infection. Bacterial replication was examined at 3 and 24 h in WT mast cells infected with LVS and the highly human virulent type A strain, SCHU S4, and compared with infected TLR2−/− and TLR4−/− mast cells. These analyses revealed that whereas bacterial replication of both LVS and SCHU S4 was restricted in WT and TLR4−/− mast cells, TLR2−/− mast cells exhibited significantly (*p < 0.002) increased (2–3 log) replication compared with WT mast cells at 24 h (Fig. 1). Macrophages were used for comparison, and as previously observed (33, 34), LVS and SCHU S4 replicated robustly within primary WT macrophages. These results suggest that TLR2 recognition of bacteria and/or TLR2 signaling is critical for the control of *F. tularensis* replication within mast cells.

**TLR2−/− mast cells lack detectable IL-4 production and exhibit reduced cathepsin L activation immediately following infection**

Given that we have previously demonstrated that IL-4 is critical for mast cell inhibition of *F. tularensis* replication (33), and that TNF-α has been suggested to be an important innate immune component in host defense (40, 41), supernatants collected from WT, TLR2−/−, and TLR4−/− mast cells during mock or LVS infection
were analyzed for IL-4 and TNF-α production. Both IL-4 and TNF-α were produced by LVS-infected WT and TLR4−/− mast cells, whereas TLR2−/− mast cells lacked detectable IL-4 production, but produced similar levels of TNF-α to WT mast cells (Fig. 2A). LVS-infected TLR4−/− mast cells exhibited marked reduction of TNF-α production compared with WT and TLR2−/− mast cells (Fig. 2A). Given that LVS- or SCHU S4-infected TLR2−/− mast cells exhibited marked susceptibility to the organisms, but impaired IL-4 production in contrast to WT or TLR4−/− mast cells, additional studies were focused on the contribution of TLR2.

Because IL-4 treatment increases phagosome acidification during Francisella infection (34), and the hydrolytic protein cathepsin L has been shown to be enhanced by IL-4 (42), we subsequently analyzed the expression of cathepsin L by flow cytometry. These analyses revealed reduced active cathepsin L expression in TLR2−/− LVS-infected mast cells (Fig. 2B; 55.0%, representative histogram shown) at early time points (30 min shown; filled lines) compared with WT (86.0%, representative histogram shown). However, by 1 h after LVS challenge (Fig. 2B; hatched lines), cathepsin L decreased in WT (12.5%, representative histogram shown) and increased in TLR2−/− mast cells (95%, representative histogram shown). Taken together, these results suggest that TLR2 recognition of Francisella and downstream signaling are important for IL-4 production and subsequent regulation of cathepsin L synthesis in mast cells.

TLR2−/− mast cells express altered LAMP and MHCII trafficking and acidification during F. tularensis infection

Because IL-4 has been shown to upregulate MHCII expression and acidification in macrophages (34, 43), and given that accumulation of LAMP2 is important during phagosome maturation and ensuing phagosome/lysosome fusion (21, 44), MHCII and LAMP2 were examined in Lucifer yellow-labeled LVS-infected WT, TLR2−/−, and TLR4−/− mast cells. Flow cytometry analysis of MHCII surface expression during early (30 min) LVS infection revealed that WT mast cells express reduced MHCII surface proteins (22%) compared with TLR2−/− mast cells, which expressed almost twice (41%) the level and were comparable to TLR4−/− mast cells (37%) (Fig. 3A). We then used confocal microscopy to examine the relationship between MHCII and colocalization with labeled LVS. Interestingly, confocal microscopy analysis revealed that
whereas TLR2<sup>−/−</sup> mast cells showed high levels of MHCII expression at the cell surface, intracellular MHCII expression was markedly reduced and greater numbers of LVS were present in the TLR2<sup>−/−</sup> mast cells, in contrast to WT mast cells, which showed high levels of intracellular MHCII along with reduced Lucifer yellow-labeled bacteria (Fig. 3B). For further examination, we used three-dimensional confocal microscopy analysis at a higher magnification (×1000) and visualized notable aggregation of MHCII molecules with LAMP2-positive proteins in WT mast cells early (30 min) during LVS infection, in contrast to TLR2<sup>−/−</sup> mast cells with dispersed MHCII and LAMP2-positive proteins throughout the cells (Fig. 4A). However, by 3 h LAMP2 and MHCII trafficking to the cell surface increased, along with decreased c-Kit-positive fluorescent proteins in TLR2<sup>−/−</sup> mast cells, when compared with WT mast cells (Fig. 4B). Moreover, increased levels of Lucifer yellow-labeled bacteria in TLR2<sup>−/−</sup> mast cells also were noted compared with WT mast cells (Fig. 4B), which was in agreement with bacterial plate counts (Fig. 4C). Because TLR2<sup>−/−</sup> mast cells exhibited increased LVS replication and reduced colocalization with MHCII and acidification marker, we analyzed cell death by examining active caspase-3 induction as well as the effect of rIL-4 on these processes. Importantly, LVS- and SCHU S4-infected TLR2<sup>−/−</sup> mast cells exhibited a significant increase in active caspase-3 expression when compared with similarly infected WT or TLR4<sup>−/−</sup> mast cells (Fig. 4C, only SCHU S4 shown), whereas addition of rIL-4 to the TLR2<sup>−/−</sup> mast cells reduced active caspase-3 induction and conferred control of SCHU S4 bacterial replication similar to WT mast cells. These results suggest that mast cell TLR2 recognition of *F. tularensis* and consequential downstream signaling promote phagosome maturation, trafficking of LAMP2 and MHCII molecules, and killing of *Francisella*, which is likely related to IL-4 signaling. Addition of rIL-4 rescued SCHU S4-infected TLR2<sup>−/−</sup> mast cells from apoptosis and promoted effective killing of the organism.

**FIGURE 3.** MHCII and LAMP2 expression are altered in TLR2<sup>−/−</sup>-deficient mast cells. (A) WT, TLR2<sup>−/−</sup>, and TLR4<sup>−/−</sup> mast cell MHCII surface analysis by flow cytometry. Representative histograms are shown. (B) WT, TLR2<sup>−/−</sup>, and TLR4<sup>−/−</sup> mast cells infected with Lucifer yellow-labeled LVS (green) and labeled with c-Kit (purple) surface fluorescent-conjugated Ab with intracellular MHCII (light blue), LAMP2 (orange), and acidification probe (red). Representative images are shown at 30 min. Original magnification ×400.
mast cells were polarized, highly mobile, and efficient in killing of Lucifer yellow-labeled LVS in contrast to TLR2/−/− mast cells. Furthermore, live cell imaging of TLR2/−/− mast cells (Supplemental Video 2) demonstrated that the cells efficiently engulf Lucifer yellow-labeled LVS (green); however, bacteria did not localize within acidified regions (red), and instead persisted (green) within the mast cells. Sequential images of WT mast cells (Supplemental Fig. 1A–D) show polarized acidification regions (white arrows) during phagocytosis of bacteria, in contrast to TLR2/−/− mast cells with acidification regions around the mast cell periphery (Supplemental Fig. 1E–H, lower panel, white arrows). Collectively, the live cell imaging of WT mast cells (Supplemental Video 1) revealed rapid phagocytosis, acidification (red), and degradation of LVS (green), suggestive of a more efficient phagosome and phagolysosomal maturation process. Importantly, these results are in agreement with bacterial plate count information showing that TLR2/−/− mast cells efficiently engulf Francisella, but permit survival and growth of the organisms, whereas WT mast cells demonstrate effective killing of the pathogen.

Discussion
Mast cells provide a dynamic defense against mucosal pathogens. Control of certain bacterial pulmonary pathogens, including F.
Francisella tularensis (30, 32, 45), Mycobacterium tuberculosis (46), and Pseudomonas aeruginosa (47, 48), requires TLR2 receptor signaling. This study provides further mechanistic insight into mast cell bacterial recognition and control of infection.

Importantly, mast cell TLR2-mediated innate immune responses included optimal trafficking and early accumulation of LAMP2, MHCII, and cathepsin L, which resulted in effective killing of F. tularensis. TLR signaling and subsequent lysosomal function has been primarily characterized in dendritic cells (49). Trombetta et al. (13) used LPS to demonstrate that mature dendritic cells accumulate vacuolar pumps, resulting in enhanced acidified lysosomes and Ag proteolysis. These dendritic cells also were shown to accumulate MHCII molecules. Blander and Medzhitov (50) later demonstrated that dendritic cell TLR4 recognition of LPS to accumulate vacuolar pumps, resulting in enhanced acidification of lysosomes (apoptotic cells) and non-self for Ag presentation. In contrast, Yates and Russell (36) have proposed that phagosome maturation occurs independently of TLR2 or TLR4 stimulation, using bone marrow-derived macrophages stimulated with Pam3Cys-Ser-Lys (4 synthetic lipoprotein) or LPS. Although there may be multiple differences in the in vitro systems noted above, IL-4 was a principal component required for mast cell activity in our study. We previously have demonstrated that bone marrow-derived macrophages are highly permissive to Francisella infection; however, coculture with mast cells or the addition of rIL-4 markedly reduced bacterial replication (33, 34). Importantly, we noted that bone marrow-derived macrophages did not produce IL-4 during infection, in contrast to bone marrow-derived mast cells. We also have provided evidence that in mast cell/macrophage coculture, the production of IL-4 by mast cells promotes macrophage ATP production and subsequent phagosome acidification (34). Therefore, the differences noted by Yates and Russell (36) may have been partially due to the lack of IL-4 production by macrophages.

Previous studies (51–53) have shown that IFN-γ and TNF-α are primary control mechanisms during Francisella infection. Whereas addition of IFN-γ also improved killing of LVS in mast cells and increased IL-4 production (data not shown), TNF-α was not sufficient to induce Francisella killing in mast cells as demonstrated by TLR2−/− mast cells, which produced comparable levels to WT mast cells. Although reactive oxygen species induced by TNF-α have been shown to promote signaling via the IL-4 receptor pathway, TNF-α is not required for initiation of IL-4 signaling (54). IL-4 enhances ATP production (55), cathepsin L activation (42), and phagosome acidification (34). Additionally, our findings suggest that TLR2 signaling was required for induction of mast cell IL-4 secretion, optimal cathepsin L activation, and phagosome maturation, resulting in localization of LAMP2 and MHCII molecules with F. tularensis. It has previously been demonstrated that bone marrow-derived mast cells from WT and TLR4−/− mice produced similar levels of both TNF-α and IL-4 when stimulated with peptidoglycan from Staphylococcus aureus, whereas similarly stimulated TLR2−/− mast cells produced neither cytokine (56). This is in agreement with our observation of the lack of IL-4 in Francisella-infected TLR2−/− mast cells. The observed TNF-α production within TLR2−/− mast cells may be attributed to the induction of other TLRs, including TLR4. Importantly, TLR2 signaling has been reported to link phagocytosis to autophagy and requires acidification (57, 58). To this end, the seminal work of Heuser (35) demonstrated that cellular acidic and alkaline conditions influence lysosome trafficking along microtubules. Our findings suggest that cathepsin L activity, which targets multiple cellular proteins implicated in trafficking such as dynamin (59) and actin (60), must also be regulated in a manner for efficient movement and maturation of the phagosome/lysosome to ensure destruction of Francisella, as overexpression is associated with induction of apoptosis and tissue damage (24, 61).
Furthermore, TLR2 signaling has been reported to be important for control of M. tuberculosis (46). Effective control of this pathogen also may be dependent on ensuing acidification required for TLR9 conformational changes and subsequent function (62). Results from work reported in this study support a probable link for TLR2 signaling and ensuing acidification for TLR9 function.

Given that early TLR2 signaling and phagosome maturation were key to efficient mast cell bacterial killing, this study provides additional avenues to exploit for control of intracellular bacterial pathogens. TLR2 signaling and IL-4 production resulted in early TLR9 conformation changes and subsequent function (62).

**Disclosures**

We thank the University of Texas at San Antonio Research Centers in Minority Institutions Research Core staff and Dr. Colleen Witt for confocal microscopy analyses.

**Acknowledgments**

The authors have no financial conflicts of interest.

**References**


15. Given that early TLR2 signaling and phagosome maturation were key to efficient mast cell bacterial killing, this study provides additional avenues to exploit for control of intracellular bacterial pathogens. TLR2 signaling and IL-4 production resulted in early TLR9 conformation changes and subsequent function (62).

16. The authors have no financial conflicts of interest.

17. Acknowledgments

We thank the University of Texas at San Antonio Research Centers in Minority Institutions Research Core staff and Dr. Colleen Witt for confocal microscopy analyses.

18. Disclosures

The authors have no financial conflicts of interest.


