Intracellular Invasion of Orientia tsutsugamushi Activates Inflammasome in ASC-Dependent Manner

The Harvard community has made this article openly available. Please share how this access benefits you. Your story matters.

Citation

Published Version
doi:10.1371/journal.pone.0039042

Citable link
http://nrs.harvard.edu/urn-3:HUL.InstRepos:10436328

Terms of Use
This article was downloaded from Harvard University’s DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA
Intracellular Invasion of *Orientia tsutsugamushi* Activates Inflammasome in ASC-Dependent Manner

Jung-Eun Koo1,2, Hye-Jin Hong1,2, Andrea Dearth3, Koichi S. Kobayashi3,4*, Young-Sang Koh1,2*

1 Department of Microbiology and Immunology, Brain Korea 21 Program, Jeju National University School of Medicine, Jeju, Jeju-Do, South Korea, 2 Institute of Medical Science, Jeju National University, Jeju, Jeju-Do, South Korea, 3 Department of Cancer Immunology and AIDS, Dana-Farber Cancer Institute, Boston, Massachusetts, United States of America, 4 Department of Microbiology and Immunobiology, Harvard Medical School, Boston, Massachusetts, United States of America

Abstract

*Orientia tsutsugamushi*, a causative agent of scrub typhus, is an obligate intracellular bacterium, which escapes from the endo/phagosome and replicates in the host cytoplasm. *O. tsutsugamushi* infection induces production of pro-inflammatory mediators including interleukin-1β (IL-1β), which is secreted mainly from macrophages upon cytosolic stimuli by activating cysteine protease caspase-1 within a complex called the inflammasome, and is a key player in initiating and maintaining the inflammatory response. However, the mechanism for IL-1β maturation upon *O. tsutsugamushi* infection has not been identified. In this study, we show that IL-1 receptor signaling is required for efficient host protection from *O. tsutsugamushi* infection. Live *Orientia*, but not heat- or UV-inactivated *Orientia*, activates the inflammasome through active bacterial uptake and endo/phagosomal maturation. Furthermore, *Orientia*-stimulated secretion of IL-1β and activation of caspase-1 are ASC- and caspase-1- dependent since IL-1β production was impaired in Asc- and caspase-1-deficient macrophages but not in Nlrp3-, Nlrc4- and Aim2-deficient macrophages. Therefore, live *O. tsutsugamushi* triggers ASC inflammasome activation leading to IL-1β production, which is a critical innate immune response for effective host defense.

Introduction

*Orientia tsutsugamushi*, an obligate intracellular bacterium which is transmitted by the bite of the larvae of certain trombiculid mites, is the causative agent of scrub typhus (tsutsugamushi disease). Scrub typhus is characterized by fever, rash, eschar, pneumonia, meningitis, and disseminated intravascular coagulation and often becomes fatal due to severe multiple organ failure without appropriate treatment [1,2]. *O. tsutsugamushi* usually infects endothelial cells, macrophages, polymorphonuclear leukocytes (PMN), and lymphocytes in patients or in animal models [3–7]. Proinflammatory cytokines, such as TNF-α, IL-1β and interleukin-6 (IL-6), increase markedly in patients with scrub typhus, and attribute to the high fever occurring in most scrub typhus patients [9]. Such host responses against *O. tsutsugamushi* may involve the activation of specialized pattern recognition receptors (PRR) in the cells, leading to the production of proinflammatory mediators.

The innate immune system provides the first line of protection against pathogens. Major functions of the innate immune system include recruiting immune cells to sites of infection and the activation of the complement cascade and the adaptive immune system. Host immune cells sense microbial infection using pattern recognition receptors (PRR) that recognize molecular signatures known as pathogen-associated molecular patterns (PAMPs) [9]. PRRs include Toll-like receptors (TLRs), NLR or nucleotide binding domain (NBD), leucine rich repeat (LRR) family of proteins [10,11] and retinoid acid-inducible gene I (RIG-I)-like receptors (RLRs) and contribute to immune activation in response to diverse stimuli, including infection or tissue injury [12]. These PRRs are expressed either on the cell membrane or in endosomal compartments or the cytoplasm.

Recent studies have shown the existence of a cytosolic detection system for intracellular PAMPs. These intracellular PAMPs are also recognized by a PRR family of cytosolic NLRs. NLRs consist of three domains characterized by an amino-terminal protein interaction domain, a central nucleotide-binding domain and a carboxy-terminal LRR (leucine-rich repeat) domain [13]. NLR proteins can be subclassified by their N-terminal protein interaction domains into CARD containing (NLRC), Pyrin containing (NLPR) or other NLR family proteins [11]. So far, at least 23 human and 34 murine NLR genes have been identified, although the physiological function of most NLRs remains poorly understood [14]. With the exception of Nod1 and Nod2, which are involved in the activation of inflammatory gene expression, several NLRs are involved in the activation of caspase-1-activating complexes called inflammasomes [15]. These NLRs, including Nlrp1, Nlrp3 and Nlrc4, respond to various PAMPs or damage associated molecular patterns and lead to the release of the IL-1 family of inflammatory cytokines including IL-1β, IL-18 and IL-33 through the formation of the inflammasome [16]. Nlrp1 senses the *Bacillus anthracis* lethal toxin, which is delivered into the cytoplasm by receptor-mediated endocytosis [17]. Nlrc4 senses bacterial...
flagellin and components of the type III secretion system (TSSS) such as Preg-like protein through Naip3 and Naip2, respectively [18,19]. Nip3 senses exogenous and host danger signals such as pore-forming toxins, extracellular ATP and crystals such as uric acid, cholesterol, silica, asbestos or alum [20]. Activation of the inflammasome also causes programmed cell death called pyroptosis, which contributes to the elimination of pathogen-infected cells [21]. The inflammasome consists of NLRs, caspase-1 and the adaptor protein apoptosis-associated speck-like protein containing a caspase-activating CARD (ASC). Caspase-1, also known as IL-1β-converting enzyme, mediates the processing of the pro-form of these cytokines into mature forms, which results in the secretion of bioactive cytokines. ASC bridges the interaction between NLRs and caspase-1 in the inflammasome complexes by mediating homotypic interactions with its amino-terminal pyrin domain and carboxy-terminal CARD [22]. ASC has a specific role in caspase-1 activation, because secretion of TNF-α and IL-6 is not affected by ASC deficiency [23]. Recently, the absent in melanoma 2 (AIM2) has been identified as a novel inflammasome component involved in the recognition of cytosolic DNA during viral and bacterial infection such as Listeria monocytogenes and Francisella tularensis [24–30]. AIM2 is a type I IFN-inducible cytosolic protein containing an amino-terminal pyrin domain and a domain of carboxy-terminal hematopoietic interferon-inducible nuclear antigens with 200 amino acid repeats (HIN200) [24]. The HIN domain promotes binding of DNA, whereas the pyrin domain associates with ASC and forms the caspase-1-activating inflammasome. Like other inflammasomes, AIM2 leads to the processing and release of mature IL-1β and IL-18 and host cell death called pyroptosis via the activation of caspase-1.

Although O. tsutsugamushi infection induces severe inflammation accompanied with the production of proinflammatory cytokines including IL-1β, the mechanism by which O. tsutsugamushi activates innate immune responses has not been elucidated. In this study, we demonstrate that IL-1 receptor signaling is critical for effective host defense during O. tsutsugamushi infection. Furthermore, we found that the uptake of live bacteria by macrophages is essential for O. tsutsugamushi-induced inflammasome activation, which results in the release of IL-1β in an ASC adaptor protein- and caspase-1-dependent manner.

Results

IL-1 Receptor Signaling is Required for Effective Host Defense Against O. tsutsugamushi (OT) Infection

To determine which proinflammatory cytokines play a critical role in host defense during OT infection, C57BL/6 mice were intraperitoneally infected with OT, and the mortality, splenomegaly and cytokine level in the serum were examined. The OT-infected mice did not show any clinical signs by day 6 post-infection. After this asymptomatic period, the mice became increasingly sick and were seriously ill by day 10 with increased amounts of ascites. The mice then gradually recovered afterwards and appeared normal by day 19. During the course of the disease, the mice developed splenomegaly that progressively became severe (Figure 1A). We found that OT infection induced IL-1β release in the serum, which peaked on day 6 (Figure 1B). The elevation of serum IL-1β levels seems partially due to increased transcripts of IL-1β, since mRNA levels of IL-1β and related cytokine IL-18 in the spleen assessed by RNA protection assay increased after OT infection, together with IL-1α and MIF, and peaked on day 4 (Figure 1C). This finding of IL-1β release during OT infection prompted us to examine the role of IL-1 receptor signaling in host defense against OT infection. We challenged wild-type and IL-1 receptor (IL-1R) deficient mice with OT and quantified bacterial numbers in the blood and spleen using qPCR. OT was detected in both blood and spleen in wild-type mice on day 6 and this bacterial load decreased by day 19 (Figure 1D). Strikingly, we found that IL-1R deficient mice were highly susceptible to OT, as demonstrated by the significantly elevated numbers of OT in both the blood and spleen, indicating that IL-1 receptor signaling is important for effective protection of hosts from OT infection.

Live O. tsutsugamushi Infection Activates IL-1β Processing and Secretion

Since macrophages are a major source of IL-1β, we examined whether OT infection in macrophages in vitro can induce IL-1β release. LPS-primed BMDMs were infected with OT and levels of IL-1β release in the supernatant was assessed. As shown in Figure 2A and B, OT infection induced release of IL-1β in a time- and dose-dependent manner in LPS-primed BMDMs. The level of IL-1β secretion peaked 6 h postinfection and was proportional to the bacterial dose (ICU) (Figure 2A and B). Based on these results, we optimized the conditions for assessing IL-1β levels from OT-infected macrophages, and those conditions were used for further analysis.

In the current model of IL-1β maturation, two independent signals are required for production and secretion of active IL-1β [15]. The first signal is induced through plasma membrane-associated PRRs such as TLRs to activate transcription of pro-IL-1β, and the second signal is mediated by the NLR inflammasomes that induce cleavage of IL-1β precursors into the active forms through caspase-1 activation [31]. To determine whether OT provides the first or second signal, BMDMs were infected with live or inactivated bacteria in the presence or absence of priming with LPS. First, BMDMs were challenged with live, heat-inactivated or UV-inactivated OT for 16 h and then stimulated with ATP for IL-1β secretion. Although LPS-primed BMDMs released IL-1β, BMDMs pretreated with live or inactivated OT failed to effectively produce IL-1β upon ATP stimulation, indicating that OT, live or inactivated, provides a first signal at only modest levels to prime macrophages to synthesize pro-IL-1β (Figure 2C). Next, BMDMs were primed with LPS and challenged with ATP, or live or inactivated OT to determine whether OT infection provides a second signal for the processing and release of IL-1β. Live bacteria or ATP induced significant IL-1β release, but not heat- or UV-inactivated bacteria (Figure 2D). This suggests that only live OT was able to activate caspase-1 to induce IL-1β maturation and secretion. To confirm this, the OT-induced caspase-1 activation was assessed by western blot analysis. In addition to ATP-stimulated or Salmonella-infected BMDMs, the p10 fragment, a subunit of active caspase-1, was detected in BMDMs upon infection with live OT (Figure 2E). Taken together, these data suggest that OT activates caspase-1 and induces IL-1β secretion in macrophages.

Phagocytosis of O. tsutsugamushi and Phagosomal Acidification were Required for IL-1β Release

Since O. tsutsugamushi are obligatory intracellular bacteria, it is an interesting question to ask if intracellular invasion of OT is required for the activation of caspase-1. First, to determine whether phagocytosis is required for IL-1β secretion by BMDMs infected with OT, cells were pretreated for 1 h with various doses of actin polymerization inhibitor, cytochalasin D (CD), to inhibit phagocytosis. The CD treatment efficiently blocked Orientia internalization (data not shown). CD pretreatment reduced mature IL-1β release from LPS-primed BMDMs
Figure 1. IL-1 receptor signaling is required for effective host protection from *O. tsutsugamushi* infection. (A) C57BL/6 mice (*n* = 5) were i.p. inoculated with *O. tsutsugamushi* (OT) (5 × 10⁶ IUC) for the indicated time periods. Spleens were removed from infected mice and their weights were measured and normalized to body weight. (B) Serum IL-1β levels from infected mice were assessed by ELISA. A single circle represents an individual animal, and lines indicate the mean values. **p < 0.01, ***p < 0.001 versus uninfected mice. (C) Cytokine mRNA expression in the spleen from infected mice. At the indicated time periods after infection, total RNA was extracted and mRNA expression was determined by RNase protection assay. L32, a murine ribosomal protein; GAPDH, glyceraldehyde-3-phosphate dehydrogenase. (D) Age and sex-matched wild-type (WT, *n* = 7) and IL-1R-deficient mice (*n* = 7) were infected with *O. tsutsugamushi* i.p. for 6 and 19 days. *O. tsutsugamushi* loads in blood and spleen were quantified by qPCR using primers specific for the *O. tsutsugamushi* tsa56 gene. Data were normalized by qPCR data for the GAPDH gene in host genomic DNA. A single circle represents an individual animal, and lines indicate the mean values. *p < 0.01*, Wild-type vs. IL-1R−/−. Data are representative of three independent experiments in A-C. doi:10.1371/journal.pone.0039042.g001
infected with OT in a dose-dependent manner but did not affect ATP-induced IL-1β release (Figure 3A). On the other hand, TNF-α release in response to live OT was not affected by CD pretreatment. These results further demonstrate that live intracellular Orientia organisms are required to process IL-1β. Next, to examine if phagosomal acidification is important for OT-induced IL-1β secretion, ammonium chloride, a chemical agent that blocks endosome acidification, was added to the culture. NH4Cl treatment reduced IL-1β release from both OT infected and ATP treated macrophages in a dose-dependent manner, indicating that endo/phagosomal maturation is required for IL-1β secretion upon OT infection (Figure 3B). There was no significant change in TNF-α levels upon NH4Cl treatment. Therefore, these data demonstrate that IL-1β processing upon OT infection requires active uptake of living bacteria and maturation of phagosomes.

Caspase Activation is Essential for IL-1β Release from OT-infected Macrophages

To investigate whether OT-infected BMDMs require caspase activation for release of IL-1β, the pan-caspase inhibitor, Z-VAD-FMK was used. First, we performed immunofluorescence microscopy and MTT assay in order to test whether Z-VAD-FMK has any inhibitory effect on bacterial internalization into host cells and host cell viability. The LPS-primed BMDMs were pretreated with various doses of Z-VAD-FMK, and then infected with OT. Z-VAD-FMK did not interfere with internalization of OT into the cells (Figure 4A). Furthermore, the indicated concentration of

---

**Figure 2. Live O. tsutsugamushi infection activates caspase-1 and induces IL-1β secretion in LPS-primed BMDMs.** (A, B, D) BMDMs were primed with LPS (10 ng/ml) for 16 h and infected with OT. IL-1β release was assessed by ELISA. (A) LPS-primed BMDMs were treated with ATP (5 mM) for 3 h or infected with OT (ICU/cell = 50) for the indicated time periods. (B) LPS-primed BMDMs were infected with OT of the indicated ICU/cell for 6 h. (C) BMDMs were primed with LPS (10 ng/ml), live OT, heat-inactivated (HOT) or UV-inactivated (UVOT) for 16 h and then treated with ATP (5 mM) for 3 h. (D) LPS-primed BMDMs were challenged with ATP, live OT, heat-inactivated OT (HOT), or UV-inactivated OT (UVOT) for 6 h. (A-D) Error bars represent SD of triplicate samples. N.D.: not detected. (E) LPS-primed BMDMs were challenged with the vehicle (−), ATP (5 mM, for 3 h), Salmonella enteritidis (Sal., MOI = 25) or OT (ICU/cell = 50) for the indicated time periods. The caspase-1 activation was analyzed by western blotting using rabbit polyclonal antibodies specific for the p10 subunits of caspase-1. Data are representative of three independent experiments in A-E. doi:10.1371/journal.pone.0039042.g002
The pan-caspase inhibitor did not affect the viability of BMDMs infected with OT (Figure 4B). LPS-primed BMDMs were pretreated with Z-VAD-FMK in various concentrations, and then infected with OT or treated with ATP. The level of IL-1β in the culture supernatant was significantly reduced by treatment with the pan-caspase inhibitor (Figure 4C). On the other hand, the caspase inhibitor had no significant effect on the level of IL-6 (Figure 4C). These results suggest that activation of caspase is essential for OT-induced IL-1β secretion by BMDMs.

**O. tsutsugamushi** Infection does not Induce Pyroptotic Cell Death in Bone Marrow-Derived Macrophages

Pyroptosis is a caspase-1-dependent cell death process through ASC pyroptosome, a molecular platform to recruit and activate caspase-1, largely composed of oligomerized ASC [32]. Pyroptosis is an important protection mechanism of the host by eliminating infected cells, and various intracellular bacterial species such as *Salmonella* or *Legionella* have been shown to induce pyroptosis via caspase-1 activation [33,34]. To determine whether *O. tsutsugamushi* infection can induce pyroptosis, LPS-primed macrophages were infected with various doses of bacterium for the indicated time periods, and then culture supernatants were used for lactate dehydrogenase (LDH) release assay. The ATP treatment induced significant release of LDH into the culture medium as previously described [35,36]. However, *O. tsutsugamushi* infection did not induce pyroptosis even at high doses of bacterium in wild-type macrophages as well as *Nlrp3*, *Nlrc4*, *Aim2* and *Asc*-deficient macrophages (Figure 5 and data not shown). Therefore, *O. tsutsugamushi* infection does not induce pyroptosis, although it effectively induces the inflammasome to activate caspase-1.

Nlrp3 and Nlrc4 do not Play a Major Role in the Production of IL-1β Induced by *O. tsutsugamushi* Infection

The caspase-1 activation induced by *O. tsutsugamushi* infection suggested the possible involvement of inflammasome-forming NLRs in the detection of intracellular OT. To gain insight into the signals activated by the internalization of OT, macrophages from wild-type and mutant mice were infected with OT. To investigate whether caspase-1 activation by OT was dependent on TLR or Nod1/Nod2 signaling, *MyD88* and *Rip2*-deficient BMDMs were primed by LPS treatment, and then infected with OT or treated with ATP. IL-1β release upon ATP stimulation was not detectable in *MyD88*-deficient BMDMs but was not altered in *Rip2*-deficient BMDMs. These results were consistent with the previous reports, since TLR4 signaling via the MyD88-dependent pathway is required as a first signal for pro-IL-1β synthesis upon LPS priming (Figure 6A). Similarly, upon OT infection, wild-type and *Rip2*-deficient BMDMs produced both IL-1β and IL-6 significantly, whereas *MyD88*-deficient BMDMs did not. These suggest that MyD88-dependent signaling is required for LPS priming whereas Rip2 is not required for LPS priming and inflammasome formation in OT-infected macrophages. To determine which NLR or HIN-200 family proteins are involved in OT induced inflammasome activation, the LPS-primed macrophages from wild-type, *Nlrp3*, *Nlrc4*, or *Aim2*-deficient mice were challenged with OT or ATP, and the production of IL-1β was assessed by ELISA. The production of IL-1β induced by ATP treatment was dependent on Nlrp3, as previously shown (Figure 6B) [37,38]. However, *Nlrp3*, *Nlrc4*, or *Aim2*-deficient macrophages infected with OT produced IL-1β at a level comparable to that of wild-type macrophages (Figure 6B). All types of macrophages produced the inflammasome-independent proinflammatory cytokine IL-6 in response to OT infection.
Figure 4. IL-1β secretion induced by *O. tsutsugamushi* infection in LPS-primed BMDMs was blocked by pan-caspase inhibitor. LPS-primed BMDMs were pretreated with pan-caspase inhibitor Z-VAD-FMK (VAD) at the indicated concentration for 1 h and then challenged with ATP (5 mM) for 3 h or OT (A. ICU/cell = 10; B.C. ICU/cell = 50) for the indicated period (A) or 6 h (B, C). (A) Cells were fixed and stained with human antiserum against OT and a FITC-conjugated goat anti-human IgG antibody, and examined using a fluorescence microscope. Green spots indicate OT and red areas indicate the host cell. Scale bar, 50 μm. (B) Cell viability was measured by MTT assay. (C) The production of IL-1β and IL-6 was assessed by ELISA. Error bars represent SD of triplicate samples. **p<0.01, ***p<0.001 versus vehicle-treated cells. Data are representative of three independent experiments in A-C.

doi:10.1371/journal.pone.0039042.g004
Secretion of biologically active IL-1β requires posttranslational processing by active caspase-1. Therefore, we compared caspase-1 activation in wild-type and Nlrp3-, Nlrc4-, or Aim2-deficient BMDMs by western blotting for p10 caspase-1 subunits that are generated by autocatalytic cleavage and released from the cell by a poorly defined mechanism [39]. Culture supernatants from LPS-primed wild-type BMDMs contained the caspase-1 p10 subunit after infection with OT (Figure 6C). LPS-primed BMDMs from Nlrp3-, Nlrc4-, or Aim2-deficient mice were also able to process caspase-1 to produce the caspase-1 p10 subunit in response to OT (Figure 6C). These data indicate that Nlrp3, Nlrc4 and AIM2 do not play significant roles in the caspase-1 activation during OT infection.

Caspase-1 and ASC are Essential for *O. tsutsugamushi*-induced IL-1β Secretion in Bone Marrow-derived Macrophages

The activation of pro-caspase-1 is caused by inflammasome activation either in an adaptor ASC-dependent or –independent manner [40]. To investigate whether ASC is required for IL-1β production by OT infection, macrophages from caspase-1-deficient mice and ASC-deficient mice were primed with LPS and then challenged with OT or ATP. Caspase-1-deficient macrophages failed to produce IL-1β (Figure 7A). Similar to caspase-1-deficient macrophages, ASC-deficient macrophages, as well as dendritic cells, did not produce IL-1β (Figure 7B). Furthermore, ASC-deficient macrophages were not able to process caspase-1 upon OT infection, evidenced by the absence of active caspase-1 by western blotting analysis and flow cytometric analysis using an active caspase-1-specific probe (FAM-YVAD-FMK) (Figure 7C and D). These data indicate that caspase-1 is essential for secretion of IL-1β in response to cytosolic *Orientia* and identify ASC as the critical inflammasome adaptor for caspase-1 activation in response to OT infection.

Discussion

The innate immune cells recognize pathogenic microbial invasion and produce proinflammatory cytokines such as IL-1 and TNF-α to activate the immune system and cause inflammation. In this study, we found that OT infection induces ASC inflammasome activation and IL-1β secretion which is a key innate immune response against bacterial invasion. Indeed, IL-1 receptor signaling is important for the host defense since IL-1R deficient mice were susceptible to OT infection. Interestingly, live OT but not inactivated OT induces caspase-1 activation and IL-1β secretion in LPS-primed BMDMs (Figure 2). The OT exploits integrin-mediated signaling and the actin cytoskeleton for internalization of host cells (Figure 6) [41]. The actin polymerization inhibitor effectively blocked IL-1β processing and release by OT infection (Figure 3A). Following internalization, the phagosome is transformed into a phagolysosome through a progressive maturation process that is dependent on the sequential fusion of lysosomes with the internalized phagosome (Figure 8) [42,43]. After internalization into the host cell by endosomal/phagocytosis, OT escapes from the late endo/phagolysosome to the cytosol (Figure 8) [44]. Although the mechanism behind this OT escape from the endo/phagolysosome is not clear, it has been shown that OT escapes from the endosome and the infectivity of OT is impaired in the presence of inhibitors for endosomal maturation such as NH4Cl or bafilomycin. Thus, the acidification of endocytic compartments is required for the efficient OT infection [44]. Interestingly, endosomal acidification inhibitor-treated BMDMs reduced release of IL-1β by *Orientia* infection (Figure 3B). Therefore, OT internalization and phagosomal acidification are required for IL-1β release by BMDMs. These findings suggest that OT-induced IL-1β secretion requires bacterial escape from the phagosome to the cytosol where the bacterium replicates and the PAMPs of OT may activate one of NLRs in the cytoplasm (Figure 8). In case of infection of *Ehrlichia muris*, another obligate intracellular bacterium in the family of Anaplasmataceae, BMDMs do not induce IL-1β secretion, probably because *E. muris* resides in endosomal compartments and does not escape into the cytosol [45]. Another possible mechanism behind how OT activates cytoplasmic innate immunity might be due to the secretion of active PAMPs by a type IV secretion system [46]. In this case, however, it is not clear why acidification of phagosomes is required for caspase-1 activation.

IL-1β secretion from OT-infected BMDMs indicates that component(s) of the inflammasome may recognize this bacterium in the cytosol. Although Asc- or caspase-1-deficient BMDMs did not induce IL-1β secretion, the OT infection-induced IL-1β secretion and caspase-1 activation were not affected by Nlrc4-, Nlrp6-, or Aim2-deficiency (Figure 6). ASC is an adaptor protein which interbridges between Pyrin domain containing cytoplasmic sensor and CARD domain containing caspase-1. Therefore, it is likely that Pyrin containing NLR may play an important role in cytosolic detection of OT. Our data indicate that Nlrp3 is unlikely to be the candidate (Figure 6). Thus, it is unlikely that Nlrp3-activating factors such as potassium efflux, generation of reactive oxygen species or cytoplasmic release of lysosomal enzymes are associated with OT-induced inflammasome activation. Also, we have not seen the reduction of IL-1β production in Nlrc4- and Nlrp6-deficient macrophages (data not shown). Since macrophages are major producer of IL-1β, these data suggests that Nlrp3, Nlrp6, Nlrp12, Nlrc4 and Aim2 are unlikely to be involved in OT-induced inflammasome activation. In human, 14 out of 23 NLRs are Pyrin containing NLR (NLRP) and more exists in mouse. Further analysis is required for the identification of OT-sensing NLR in the cytoplasm.

Although live OT can activate inflammasome, OT, whether live or not, were not very effective in priming macrophages for subsequent stimulation for IL-1β production (Figure 2C). We found that in vivo infection of OT induced IL-1β in the serum, suggesting that OT is able to do both priming and inflammasome activation during in vivo infection. Perhaps OT can prime cells more efficiently via TLR signaling in vivo than in vitro in BMDMs, and this results in the IL-1β production in OT infected animals.
Another interesting possibility is that priming of cells during *in vivo* OT infection may be enhanced by cytokine signaling through positive feedback loop via the production of proinflammatory cytokines such as TNF-α.

It has been demonstrated that caspase-1 activation also leads to cell death called pyroptosis during microbial infection [32]. Pyroptosis mediates further activation of inflammatory response by the innate immune system. Upon infection by intracellular

**Figure 6. *O. tsutsugamushi* activates caspase-1 in LPS-primed BMDMs in Nlrp3-, Nlrc4- and AIM2-independent manners.** Wild-type (WT), MyD88−, Rip2−, Nlrp3−, Nlrc4− or Aim2−deficient BMDMs were primed with LPS (10 ng/ml) for 16 h and then treated with ATP (5 mM) for 3 h or infected with OT (ICU/cell = 50) for 6 h or the indicated time periods. (A, B) IL-1β and IL-6 production from the cells was assessed by ELISA. (C) The cleaved caspase-1 and pro-caspase-1 were analyzed by western blotting using rabbit polyclonal antibodies specific for the p10 subunits of caspase-1. Error bars represent SD of triplicate samples. N.D.; not detected. **p<0.001 versus wild-type. Data are representative of three independent experiments in A-C. doi:10.1371/journal.pone.0039042.g006
bacteria or viruses, infected cells form an ASC pyroptosome, which rapidly recruits and activates caspase-1 resulting in pyroptosis and the release of the intracellular proinflammatory cytokines [32]. *Franciella tulerensis*, for instance, activates AIM2 inflammasome leading to IL-1β processing and pyroptosis through ASC pyroptosome formation [29]. *Legionella* spp induce pyroptosis via Nlrc4/Birc1e inflammasome in general, however, *Legionella* strains which do not induce pyroptosis, such as *L. parisiensis* or *L. tucsonensis* or flagellin-defective *L. pneumophila*, can replicate efficiently in macrophages, indicating critical roles of pyroptosis for host defense [47]. Interestingly, although OT infection activates caspase-1, OT-infected macrophages did not release the LDH significantly, which is different from other bacteria that induce pyroptosis (Figure 5).

**Materials and Methods**

**Bacteria and in vitro Orientia tsutsugamushi Infection of Cells**

The prototype strain, *Orientia tsutsugamushi* Boryong was propagated in monolayer of L-929 cells (American Type Culture Collection) as described previously [49]. When more than 90% of the cells were infected, the cells were collected, homogenized with a glass Dounce homogenizer (Wheaton Inc., NJ, USA), and centrifuged at 500 × g for 5 min at 4°C. The supernatant was recovered and stored in liquid nitrogen until use. The infectivity
The titer of the inoculum was determined as described previously [49]. Briefly, five-fold serially diluted oriential samples were inoculated onto L-929 cell layers on 24-well tissue culture plates. After 3 days of incubation, the cells were collected, fixed, and stained using an anti-orientia antibody. The ratio of infected cells to the counted number of cells was determined microscopically, and infected-cell counting units (ICU) of the oriential sample were calculated as follows: ICU = (total number of cells used in infection) × (percentage of infected cells) × (dilution rate of the orientiae suspension)/100. Heat-inactivation of bacterial inoculum was performed by heating OT at 56°C for 30 min. UV-inactivated bacterial inoculum was obtained by exposure to 254 nm wavelength UV of 4 mW·sec/cm² for 30 min.

In the inhibition assays, BMDMs were primed with LPS (from Salmonella minnesota, Alexis, NY, USA) for 16 h, then were preincubated with cytochalasin D (CD; Sigma, MO, USA), ammonium chloride (NH₄Cl, Sigma), or Z-VAD-FMK (Calbiochem, NJ, USA), for 1 h before OT was inoculated. Inhibitors were maintained for the course of inhibition assays. After 1 h incubation, cells were infected with OT for the indicated time periods. Cell viability was determined by 3-(4,5-dimethyl-2,5-thiazolyl)-2,5-diphenyl tetrazolium bromide (MTT) assay and was not affected by doses of the inhibitors used in this study.

Mice

MyD88-, Rip2-, caspase-1-, ASC-, Nlr4-, Nlrp3-, and Aim2-deficient mice were established as described, and the mice or femurs were kindly provided by Drs. Shizuo Akira (Osaka University), Richard Flavell, Yasunori Ogura (both at Yale University), Vishva Dixit, Sanjeev Mariathasan (both at Genentech), Katherine Fitzgerald and Vijay Rathinam (both at University of Massachusetts) [22,26,37,51,52]. C57BL/6 mice were from Taconic Farm, Inc and Orient Bio Inc. (Gyeonggi-do, South Korea). IL-1R-deficient mice were originally provided by the Jackson Laboratory [53]. Mice were maintained under specific pathogen-free conditions. All mice were maintained and used in accordance with institutional and National Institutes of Health guidelines. All animal procedures were approved by and performed according to the guidelines of the Institutional Animal Care and Use Committee of Dana-Farber Cancer Institute (#04-044 and #04-045) and/or Jeju National University (#2010-0026).

Orientia Challenge of Mice in vivo

The female C57BL/6 mice were infected by intraperitoneal (i.p.) injection of 0.1 ml of oriential suspension (5×10⁶ ICU). On the indicated days of infection, mice were sacrificed, and whole blood and spleens were obtained.

RNase Protection Assay

Total RNA was extracted from the spleen using Trizol Reagent (Gibco BRL, Grand Island, NY) and was quantitated spectrophotometrically. Detection and semiquantitation of various murine cytokine and chemokine mRNAs were accomplished with the RibonQuant multiprobe RNase protection assay kit from PharMinGen (San Diego, CA). In brief, a mixture of [32P]UTP-labeled antisense riboprobes was generated from a panel of different cytokine or chemokine template DNAs. These panels also included templates for the murine housekeeping genes encoding GAPDH and L32 to ensure equal loading of total RNA onto the gels. Total RNAs from each sample (30 µg each) were hybridized overnight at 56°C with 3×10⁶ cpm of the 32P-labeled antisense riboprobe mixture. After hybridization, the samples were digested with a mixture of RNases A and T₁. Nuclease-protected RNA fragments were precipitated with ethanol. The samples were resolved on a 5% polyacrylamide sequencing gel. The bands were observed after autoradiography. The specific cytokine and chemokine bands were identified on the basis of their individual mobilities compared with the undigested probes.

Determination of Bacterial Load in Tissues

Since O. tsutsugamushi is an obligate intracellular bacterium that does not grow outside of the cells, quantification method for
the Orientia load using qPCR was used with a modification of previously established methods by other groups [54,55]. Briefly, the oriental load was determined by qPCR (with SYBR Green) for the Orientia 16S rRNA gene, which encodes a 56-kDa type-specific antigen of O. tsutsugamushi. Primer sequences are as follows: O. tsutsugamushi 16S forward, AACGCTATACTGTTGGACAGCAG; O. tsutsugamushi 16S reverse, ACTTTGACAGGAGACGCTTAGATG; mouse GAPDH forward, CAACCTGCTCATAGTTTC; and GAPDH reverse, CTCGCCTCTGGGACGATG. The substrate for amplification was DNA purified from cultures using the DNeasy Tissue kit (Qiagen, Valencia, CA). qPCR was performed using the 7300 real time PCR system from Applied Biosystems. Results were normalized to GAPDH levels in the same sample and expressed as relative Orientia 16S amounts per GAPDH amount.

Bone Marrow-derived Macrophages (BMDMs)

The bone marrow cells from wild-type and mutant mice were obtained from tibia and femur of mice by flushing with DMEM (Invitrogen, CA, USA) containing 10% heat-inactivated FBS, 100 U of penicillin G and streptomycin. The 1×10^7 bone marrow cells were cultured in 10 ml of DMEM containing glutamine, 20% heat-inactivated FBS, 100 U of penicillin G, streptomycin and 30% L929 cell supernatant containing M-CSF in 100 mm petri dish (BD Falcon, NJ, USA) at 37°C in humidified 5% CO2. After the indicated time periods, cell death was quantified with the CytoTox96 LDH-release kit (Promega, WI, USA). Percent of cell death is calculated measuring the OD490 of each sample and using the following formula: ([experimental cells-untreated cells]/(lysed cells-untreated cells)) ×100%.

Flow Cytometry for Active Caspase-1 Staining

Active caspase-1 staining was assessed by flow cytometry. LPS-stimulated bone marrow-derived macrophages (1×10^6 BMDMs) in non-tissue-culture-treated 12-well plates were infected for 4 h with O. tsutsugamushi (ICU/cell = 5). Cells were removed with cold PBS and stained for 1 h with FAM–YVAD–fluoromethylketone (FAM–YVAD–FMK; Immunochemistry Technologies, MN) as a substrate for caspase-1 DNA suicide assay (Bio-Rad, CA, USA) according to the manufacturer’s instructions. Data were acquired on a FACSCalibur (Becton Dickinson) and analyzed with CellQuest software (Becton Dickinson).

Cytokine Measurement

2×10^6 BMDMs were seeded onto 24-well plate, and then incubated for 24 h at 37°C in humidified 5% CO2. After treatment with LPS (10 ng/ml) for 6 h, macrophages were centrifuged at 14,000 g for 5 min at 4°C. Culture supernatants were collected from culture plates and were assayed for IL-1β (R&D system, MN, USA), IL-6 (BD Pharmingen, CA, USA), and TNF-α (R&D system) by ELISA according to the manufacturer’s instructions.
Statistical Analysis

All experiments were performed at least three times. Data are expressed as mean ± standard deviation (SD). Analysis of variance (ANOVA) was used to evaluate the data with the following significance levels: *p<0.05, **p<0.01, ***p<0.001.

References


