The Interaction Between Brucella and the Host Cell in Phagocytosis

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Abstract

Brucella spp. are facultative intracellular parasitic pathogens that can survive and multiply in professional and nonprofessional phagocytes. These pathogens are responsible for brucellosis, which can cause abortion in domestic animals and undulant fever in humans. Brucella spp. can survive in a variety of cells and their virulence and chronic infections are thought to be due to their ability to evade the killing mechanisms within host cells, one of which is the inhibition of phagosome-lysosome fusion. Lipid raft-associated molecules, such as GPI-anchored proteins, GM1 ganglioside, and cholesterol, are selectively integrated into Brucella-containing macropinosomes following the internalization of Brucella into macrophages, continuously sustaining a dynamic state of the phagosomal membrane. Toll-like receptors (TLRs) are important systems that detect microbial invasion via recognition of microbial components that triggers signaling pathways to promote the expression of genes and regulate innate immune responses. Recent several studies have revealed the importance between TLRs-Brucella interactions to control Brucella infection. Here, we reviewed selected aspects of lipid raft-associated molecules and TLRs-Brucella interaction, which may help to understand the mechanism of Brucella pathogenesis.

Keywords: Brucella, phagocytes, lipid-rafts associated molecules, TLRs, intracellular survival

1. Introduction

Brucellosis is a major zoonotic disease worldwide that causes a serious debilitating disorder in humans known as undulant fever, and abortion and sterility in domestic animals.
*Brucella* spp. are gram-negative and facultative intracellular bacteria that can survive and replicate within professional and nonprofessional phagocytes [1, 2]. Six well-recognized species of *Brucella* are known according to host preference: *B. melitensis* (sheep and goats), *B. abortus* (cattle), *B. suis* (hogs), *B. ovis* (sheep), *B. canis* (dogs), and *B. neotomae* (wood rats) [3]. In the past few years, *Brucella* has been recovered from several marine mammals, including cetaceans and pinnipeds, that belong to two potential new species, *B. pinnipedialis* and *B. ceti* [4]. Recently, a new species of *Brucella*, *B. microti*, was isolated from wild common voles suffering from a systemic disease [5, 6]. *B. melitensis*, *B. abortus*, and *B. suis* strains cause abortion and infertility in their natural hosts, goats and sheep, cattle and swine, respectively. Humans can also acquire Brucellosis in a form of a severe, debilitating febrile illness as a result of contact with infected animals or their products [7]. *B. ovis* is a natural pathogen of sheep where it primarily causes epididymitis and infertility in rams [8].

*B. canis* infection causes abortion and infertility in dogs [9]. Although *B. ovis* and *B. canis* are important in animals, human infection with *B. canis* is rare [10], and human infection with *B. ovis* has not been reported. *B. neotomae*, which infects only desert wood rats, is not known to be associated with clinical disease in any host species.

*Brucella* species, in contrast to other intracellular pathogens, do not produce exotoxins, antiphagocytic capsules or thick cell walls, resistance forms, or fimbriae and do not show antigenic variation [11]. The key aspect of the virulence of *Brucella* is thought to be due to their ability to avoid the killing mechanisms within macrophages [12, 13].

The most common points of entry of *Brucella* are the respiratory, digestive, and genital tracts of both animals and humans. *Brucella* enters the phagocytic cells in an unknown cellular site and spreads throughout the body by the regional lymph nodes. *Brucella* shows high tropism in macrophages, especially monocytes in the liver, spleen, mammary glands, and reproductive tracts. Chronic brucellosis mainly leads to bacterial resistance to host immune response and host debilitated health status [14].

A tenth of the total *Brucella* will survive to avoid phagocytosis and penetrate cell membrane for intracellular growth; macrophages are the most important for a successful infection. During the infection, *Brucella* can interfere with the macrophage function, particularly the inhibition of IFN-γ [15] and TNF-α expression [16], and the reduction of antigen presentation and subsequent T cell activation [17]. *Brucella* inside dendritic cells (DC) contributes to the chronic infection and induced low levels of pro-inflammatory cytokines and increased MHC II expression [18]. Placental trophoblasts produce erythritol during the last trimester and increases carbon source for *Brucella* and this pathogen caused abortion or stillbirth of the infected fetus by inducing placental damage [19] and targeting giant trophoblasts [20]. *Brucella* has also been reported in other cell types and are studied with cell models and lines such as human pulmonary epithelial cells, caprine uterine epithelial cells, human osteoblastic cell lines, murine neurons, bovine and human polymorphonuclear, and many other cells lines. Surprisingly, extracellular brucellae were observed on the 21st day post infection [21–26].

Phagocytosis is a critical step for a successful immune reaction against microbial pathogens that provokes both degradation of pathogens and the subsequent presentation of pathogen
peptide antigens. Ligation of various phagocytic receptors, including Fc gamma receptors and complement receptor 3, activates a series of intracellular signal transductions that induce dynamic and rapid rearrangement of the actin cytoskeleton essential for phagocytic uptake [27]. Several host cells such as M cells, macrophages, and neutrophils ingest *Brucella* by zipper-like phagocytosis [28]. In addition, *Brucella* invades macrophages through lipid raft microdomains [29]. Phagocytosis of *Brucella* in both epithelial cells and macrophages requires F-actin polymerization [30, 31].

Toll-like receptors (TLRs) are the best characterized pattern recognition receptors (PRRs) of host cells. Receptor-ligand interaction via TLRs leads to the production of antimicrobial peptides and proinflammatory cytokines through NF-κB, mitogen-activated protein kinase (MAPK), and other various signaling pathways [32]. As a result, TLR signaling is crucial to develop host innate immune response, including recruitment of DCs and T effector cells, upregulation of MHC I and II on antigen presenting cells (APCs), and extension of adaptive immunity against infection. In Brucellosis, many studies have reported that TLRs play important roles in controlling *Brucella* infection. When unopsonized *B. melitensis*, *B. abortus*, and *B. suis* strains internalize into macrophages and epithelial cells, the *Brucella*-containing vacuoles (BCVs) enter into an intracellular trafficking pathway that results in the development of specialized membrane-bound compartments [33–38] known as replicative phagosomes or brucelloosomes [39]. Interactions between the O-chain of *Brucella* smooth LPS and the lipid rafts on the surface of macrophages have been shown to be important for mediating entry into host cells in a manner that leads to the development of replicative phagosome [40]. During the initial stages of intracellular trafficking of the BCVs, these compartments suffer temporary interactions with lysosomes [41] which results in their acidification [34, 42] and initiate extensive interaction with the endoplasmic reticulum [33]. Eventually, intracellular pH rises to a level that allows intracellular replication of the *Brucella*. In epithelial cells, the BCVs during development of the replicative phagosome acquire properties resembling autophagosomes [37], which does not appear to be the case in macrophages [33]. Studies employing the human monocytic cell line THP-1 and *B. abortus* strains opsonized with hyperimmune IgG have also shown that when the *Brucella* internalizes host macrophages in this manner, the resulting BCVs also undergo temporary association with the lysosomal compartment and become acidified but do not interact extensively with the ER [43]. This altered intracellular trafficking limits the fusion of the BCVs with lysosomes, which minimizes the exposure of these bacteria to the bactericidal proteins that reside in these intracellular compartments [43].

In this section, we will discuss the key roles of several receptors for *Brucella* including immune response, signal transduction cascade, and phagocytic pathway for *Brucella* infection within host cells.

2. The roles of lipid rafts on *Brucella* infection

*Brucella* proliferates within professional and nonprofessional phagocytic host cells including macrophages, epithelial HeLa cells, fibroblasts NIH3T3, Vero cells, MDBK cells, etc., and
successfully bypasses the bactericidal effects of phagocytes [13]. The macrophage response to infection has important consequences for both the survival of phagocytized bacteria and the further development of host immunity. For many bacterial pathogens, adherence to the host tissue is believed to be essential for virulence, and the microbial characteristics that promote adherence to receptors on a host cell surface are considered to be attributes of virulence [44]. For intracellular pathogens, including Brucella, the nature of the interaction with the host cell will have important consequences for pathogen survival, proliferation, and dissemination, as well as the development of specific immunity [45]. Lipid rafts are specialized membrane microdomains rich in cholesterol, glycosylphosphatidylinositol (GPI)-anchored proteins, and GM1 gangliosides [46]. Evidence regarding the potential role of lipid rafts in host-pathogen interactions has been continuously accumulated, and lipid rafts have been implicated as portals of entry for intracellular pathogens [47]. Several studies have implicated the involvement of lipid rafts in the entry and endocytic pathway of B. abortus in host cells. These studies indicated that lipid raft-associated molecules, such as GPI-anchored proteins, GM1 ganglioside, and cholesterol, are selectively integrated into Brucella-containing macropinosomes following the internalization of Brucella into macrophages, continuously sustaining a dynamic state of the phagosomal membrane [48]. Moreover, the internalization route of Brucella into phagocytic cells determines the intracellular fate of these bacteria, and this event is modulated by lipid rafts [48].

2.1. Roles of lipid rafts-associated molecules in Brucella infection

Time-lapse videomicroscopy has been used to follow the internalization of B. abortus strains by mouse bone marrow-derived macrophages [35]. After contact of macrophages with wild-type B. abortus, the bacteria move around from the site of initial contact and swim on the macrophage surface, which often lasts up to several minutes; ruffling of the generalized plasma membrane occurs before the eventual enclosure in large vacuoles. In contrast, contact of the virB4 mutant of B. abortus with the target macrophage results in a much smaller ruffling restricted to the area near the bacteria and uptake is more rapid than for the wild-type strain. If the bacteria are deposited onto macrophages by centrifugation, generalized actin polymerization around the site of bacterial binding was observed in the wild-type strain when stained with phalloidin to detect actin filament formation by using fluorescence microscopy, which can also be observed by phase-contrast microscopy and the virB4 mutant shows primarily small regions of phalloidin staining at the sites of binding. Therefore, B. abortus appears to promote events on the macrophage cell surface that are dependent on the presence of the VirB system. In case of B. abortus, macropinocytosis occurs within minutes of attachment to bacteria on the surface of the macrophage. During bacterial contact, effector molecule(s) are translocated by the VirB system to the target cell, which initiates the process that leads to formation of the macropinosome [29, 35]. These macropinosomes are induced transiently and shrink rapidly, with the majority of vacuoles appearing tightly apposed against the bacterial surface within 20 minutes after their initial appearance. In addition, macropinosomes are probed with other components associated with lipid raft-associated molecules, such as GM1 gangliosides and cholesterol, by incubating B. abortus and biotin-labeled cholera toxin B subunit (CTB), which binds GM1-gangliosides, simultaneously with macrophages. CTB localizes around the
internalized wild-type strain with kinetics of association similar to those for aerolysin-labeled GPI-anchored proteins. In contrast, colocalization of CTB with the virB4 mutant was much less pronounced, suggesting that the formation of the VirB-dependent macropinosome includes a sorting process that allows transient association of lipid raft-associated components with macropinosomes containing *B. abortus*.

2.2. Roles of cellular prion protein in Brucella infection

In addition to membrane sorting for brucella infection, key roles have been made in describing bacterial entry where it has been shown that these bacteria penetrate into the macrophage through a particular structure found in eukaryotic cells, lipid rafts, or lipid microdomains [48]. In order to interact with lipid rafts, *Brucella* requires smooth LPS to avoid the bactericidal arsenal of macrophages that strains with rough LPS (without an O-side chain) encounter [40]. Moreover, a report has proposed that *Brucella* interacts with the cellular prion protein of macrophages (PrpC), a protein anchored by a GPI-link in lipid rafts. This interaction was found to be mediated by the membrane expression of *Brucella* HSP60 [49].

2.3. Roles of clathrin in Brucella infection

Lipid raft-associated clathrin is essential for host-pathogen interactions in infectious processes. The focus of a recent study was to elucidate the clathrin-mediated phagocytic mechanisms of *Brucella* [50]. From that study, the clathrin dependency of *Brucella* infection in HeLa cells was investigated with an infection assay and immunofluorescence microscopy. The redistribution of clathrin in the membrane and phagosomes was detected through sucrose gradient fractions of lipid rafts and the isolation of *Brucella*-containing vacuoles (BCVs), respectively (Fig. 1). Clathrin and dynamin were concentrated into lipid rafts upon *Brucella* infection, and the entry and intracellular survival of *Brucella* were abrogated by clathrin inhibition in HeLa cells. Clathrin disruption decreased actin polymerization and the colocalization of BCVs with clathrin and Rab5 but not LAMP-1. Consequently, our data verified that clathrin plays a fundamental role in the entry and intracellular survival of *Brucella* via the interaction with lipid rafts and actin rearrangement, which determines the early intracellular trafficking of *Brucella* to its advantage.

3. General aspects of toll-like receptors

Toll-like receptors (TLRs) are single-pass type I transmembrane-spanning proteins with a single intracellular Toll/interleukin-1 (IL-1) receptor (TIR) domain and multiple extracellular leucine-rich repeats (LRRs) responsible for binding to ligands that recognize and are activated by a small collection of microbe-derived molecules [51]. Through studies of targeted mutants among 13 paralogous TLRs, 10 in humans and 12 in mice, the diverse mode of ligands recognition of individual TLRs were determined, except for TLR8, TLR10 (only present in humans), and TLR11–13 (only present in mice). TLR2 is activated by lipopeptides and other gram-positive bacterial components in conjunction with either TLR1 or TLR6; TLR4 detects
LPS, which requires accessory protein MD-2; TLR5 detects flagellin; TLR3 detects poly I:C, a double-stranded RNA (dsRNA) analog; TLR9 detects unmethylated DNA and CpG-oligo-deoxynucleotides (CpG-DNA) proposed to be delivered by Granulin and high mobility group (HMG) B proteins through an ability to bind simultaneously to both CpG-DNA and TLR9; and TLR7 is activated by single-stranded RNA and its synthetic analogs such as resiquimod, imiquimod, and loxoribine. All known TLR dimer structures display the same arrangement with the two carboxy-terminal tails closely juxtaposed and the amino termini at opposite ends but each varies in modes of ligand recognition [51–54]. This conformation may be required to bring the intracellular TIR domains into close proximity to initiate signaling. TLR activation can induce cell-intrinsic antimicrobial activity such as activation of TLR2 and TLR4 can recruit NADPH oxidase assembly and mitochondria to bacteria-containing phagosome, which lead to a burst of reactive oxygen and nitrogen species within this compartment [55–57]. Evidence suggests that possibly through recruitment of vacuolar-ATPase subunits to the phagosomal membrane, TLR signaling can cause a rapid acidification of the phagosome in which TLR signaling has occurred [53, 54, 58, 59]. These activities increase the antimicrobial capacity of the phagosome, although some bacteria have actually cooped these signals to regulate their virulence programs. Expression and secretion of antimicrobial peptides (AMPs) such as β-defensins and cathelicidin can also be induced by TLRs upon detection of microbial ligands, which further supports the role of TLR-mediated detection in cell-intrinsic antimicrobial activity [60–62]. However, pathogens have evolved a variety of strategies to avoid TLR signaling such as altering their surface structures, interfering with TLR signaling pathways, and inhibiting, escaping, or subverting phagocytosis [52]. Brucella spp. are recognized by TLR2, TLR4, and TLR9, which identifies lipopolysaccharide (LPS), lipoproteins, and bacterial DNA, respectively [63].

3.1. TLRs and Brucella infection

The involvement of TLR2 and TLR4 in recognizing Brucella was reported in several studies. TLR2 was proposed to induce secretion of TNF-α, IL-6, IL-12, and IL-10 in peritoneal macrophages stimulated by B. abortus lipoproteins, such as Omp16 and Omp19 [64], responsible for pro-inflammatory response, but no role was observed in controlling the pathogen in vivo [63]. TLR4, in cooperation with TLR9, was demonstrated in B. melitensis resistance [65]. The interaction of TLR4 with non-canonical Brucella LPS induces activation of NF-κB, and its interaction with Brucella spp. lumazine synthase stimulates maturation of dendritic cells [66] followed by increased expression of co-stimulatory molecules and major histocompatibility class II, as well as the production of IL-6, TNF-α, and IL-12p70 [63].

Maturation of dendritic cells and production of IL-12 and TNF-α in macrophages and dendritic cells are impaired [67], and levels of inflammatory chemokines RANTES (CCL5), MCP-1 (CCL2) and MIP-1α (CCL) are reduced in the absence of MyD88 protein during Brucella infection [65]. MyD88 molecule is required for the development of IFN-γ producing T cells and control of brucellosis [65], suggesting that induction of Th1 response during the infection is regulated by a MyD88-dependent pathway [63]. Furthermore, this molecule is used by other
inflammatory signaling pathways that include IL-1 and IL-18 [58]. However, IL-18 was observed to have no role in controlling murine brucellosis [63].

*Brucella* appears to interfere in TLR signaling by producing inhibitory homologues of Toll/interleukin-1 receptor (TIR) domain, such as *B. abortus* Btp1, which targets TLR2 signaling down-modulating maturation of infected dendritic cells and secretion of pro-inflammatory cytokines [18], and *B. melitensis* TcpB that interacts with MyD88 in vitro impeding TLR2 and TLR4 activation pathway and secretion of pro-inflammatory cytokines [68].

### 3.2. Roles of individual TLRs in Brucella infection

#### 3.2.1. TLR2

The role of TLR2 in *Brucella* infection remains controversial. Some studies suggest that TLR2 is not required to control *Brucella* infection in the mouse [67, 69, 70]. However, other studies indicate that TLR2 is important for clearance of *Brucella* from the lung following aerosol exposure [71], cytokine production such as TNFα and IL-12 [64, 65, 67, 72, 73], MHC-II expression [74], and down regulation of the type I receptor for the Fc portion of IgG (FcγRI, CD64) [15].

#### 3.2.2. TLR4

The role of TLR4 in *Brucella* infection also remains disputed. Some studies suggest that TLR4 is required to control *Brucella* replication in the mouse [65, 69, 70], others reveal that TLR4 is not involved [67, 75]. Lee et al. [76] reported that TLR4-associated Janus kinase 2 (JAK2) activation in the early cellular signaling events plays an essential role in *B. abortus*-induced phagocytosis by macrophages (Fig. 2), implying the significance of JAK2 in pathogenesis of *Brucella* [65]. TLR2, TLR4, and MyD88 play diverse roles in *Brucella* antigen specific antibody production and antibody class switching [71].

#### 3.3. TLR6

TLR6 is an important component that triggers an innate immune response against *B. abortus*. TLR6 is recruited to the macrophage phagosome and recognizes bacterial peptidoglycan and lipoproteins [77]. TLR6 also plays a role in bacterial diacylated lipopeptides recognition such as MALP2, but is not essential for cytokine production in response to triacylated lipopeptides. TLR6, in cooperation with TLR2, recognizes *Brucella* and further activates NF-κB signaling in vitro and is required for the efficient control of *B. abortus* infection in vivo [78].

#### 3.4. TLR9

TLR9 plays a role in controlling *B. abortus* infection in mice [65, 67]. Furthermore, TLR9 partially mediates the expression of IL-12 by dendritic cells in response to heat-killed *B. abortus* [79]. TLR9 plays a significant role in preventing *B. ovis* replication in vivo, but only MyD88 is required for wild type levels of inflammation [80].
Figure 1. The role of clathrin in the entry and intracellular survival of B. abortus in non-professional phagocytes. A and B: HeLa cells were pretreated with 12.5 μM CPZ, a clathrin inhibitor, for 45 minutes prior to infection with B. abortus at an MOI of 10 for the indicated times. C–E: HeLa cells were transiently transfected with control or clathrin siRNA, whose optimal conditions were evaluated by Western blotting (C), and subsequently infected according to the procedure described above (D and E). Bacterial internalization and intracellular survival efficiency were determined by evaluating the protection of internalized bacteria from gentamicin killing and calculating the log10 CFU, respectively. The data represent the mean ± S.D. of triplicate trials from three independent experiments. Differences that were statistically significant compared with untreated samples are indicated. *, p < 0.05; **, p < 0.01; ***, p < 0.001 [50].

Figure 2. Diagram illustrating the phagocytic signaling pathway initiated by TLR4-linked JAK2 activation during the internalization of B. abortus into macrophage. The interaction of B. abortus with TLR4 induces the activation of Cdc42 GTPase and JAK2, and the subsequent activation of PI3K and MAPKs promotes actin polymerization. This event contributes to the phagocytosis of B. abortus by macrophage. Lines with arrows denote an activating reaction and dotted lines denote uncertainty of the reaction [76].
4. Conclusion

Throughout this chapter, we described the interaction between Brucella and lipid raft-associated molecules and TLRs, including interacting specific molecules (ligands), immune response, signal cascade, and controlling strategies. This review may help to understand the pathogenic and defense mechanisms of Brucellosis. Furthermore, the understanding of lipid rafts-associated molecules and TLRs-mediated controlling of intracellular parasitic bacterial infection would be helpful to eradicate these diseases.

Abbreviation

<table>
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<tbody>
<tr>
<td>IFN-γ</td>
<td>Interferon gamma</td>
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<tr>
<td>TNF-α</td>
<td>Tumor necrosis factor alpha</td>
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<td>DC</td>
<td>Dendritic cell</td>
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<td>MHC II</td>
<td>Major histocompatibility complex</td>
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<td>TLR</td>
<td>Toll-like receptor</td>
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<td>PRRs</td>
<td>Pattern recognition receptors</td>
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<td>NF-κB</td>
<td>Nuclear factor kappa-light-chain-enhancer of activated B cells</td>
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<tr>
<td>MAPK</td>
<td>Mitogen-activated protein kinase</td>
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<tr>
<td>APCs</td>
<td>Antigen-presenting cells</td>
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<td>BCVs</td>
<td>Brucella-containing vacuoles</td>
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<td>LPS</td>
<td>Lipopolysaccharide</td>
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<td>IgG</td>
<td>Immunoglobulin</td>
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<td>ER</td>
<td>Endoplasmic reticulum</td>
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<td>GPI</td>
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<td>GM1</td>
<td>Monosialotetrahexosylganglioside</td>
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<td>CTB</td>
<td>Cholera toxin B</td>
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<td>PrpC</td>
<td>Cellular prion protein</td>
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<td>HSP60</td>
<td>Heat shock protein 60</td>
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<tr>
<td>LAMP-1</td>
<td>Lysosomol-associated membrane protein 1</td>
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<tr>
<td>IL</td>
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<td>TIR</td>
<td>Intracellular Toll/interleukin receptor</td>
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<td>LRRs</td>
<td>Leucine-rich repeats</td>
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<tr>
<td>HMG</td>
<td>High mobility group</td>
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<td>NADPH</td>
<td>Nicotinamide adenine dinucleotide phosphate</td>
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<td>AMPs</td>
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<tr>
<td>Omp</td>
<td>Outer membrane protein</td>
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<tr>
<td>RANTES</td>
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<tr>
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<td>Macrophage-activating lipopeptide-2</td>
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