Role of the caspase-1 inflammasome in \textit{Salmonella typhimurium} pathogenesis

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Caspase-1 is activated by a variety of stimuli after the assembly of the ”inflammasome,” an activating platform made up of a complex of the NOD-LRR family of proteins. Caspase-1 is required for the secretion of proinflammatory cytokines, such as interleukin (IL)-1β and IL-18, and is involved in the control of many bacterial infections. Paradoxically, however, its absence has been reported to confer resistance to oral infection by \textit{Salmonella typhimurium}. We show here that absence of caspase-1 or components of the inflammasome does not result in resistance to oral infection by \textit{S. typhimurium}, but rather, leads to increased susceptibility to infection.
confirmed the genotype of caspase-1<sup>−/−</sup> mice by PCR genotyping (not depicted) and, functionally, by the resistance of their bone marrow–derived macrophages (BMDMs) to the rapid death induced by <i>S. typhimurium</i> (Fig. 1 A). The mouse <i>nramp1</i> (Slc11a1) gene controls the resistance or susceptibility of mice to several unrelated pathogens, among them <i>S. typhimurium</i> (19). Common laboratory mouse strains such as C57BL/6 and BALB/c carry a mutant <i>nramp1</i>, which renders them up to 1,000-fold more susceptible to <i>S. typhimurium</i> than strains harboring the wild-type allele (19). Knockout mouse lines are most frequently constructed using 129-derived embryonic stem (ES) cells, which have a wild-type <i>nramp1</i> allele. However, deficient animals are also frequently backcrossed into another genetic background, such as that of C57BL/6, with a mutant copy of <i>nramp1</i>. Given these considerations and because <i>nramp1</i> is the main genetic determinant of <i>S. typhimurium</i> susceptibility/resistance in mice, we determined the <i>nramp1</i> status of the control and knockout mice used in these studies. As seen in Fig. 1 B, mice carried a mutant copy of the <i>nramp1</i> gene and are therefore “Salmonella susceptible.” We used these mice to reevaluate the influence of caspase-1 in susceptibility to <i>S. typhimurium</i> oral infection. Caspase-1<sup>−/−</sup> and control mice were infected orally with 10<sup>5</sup> <i>S. typhimurium</i> (∼10 LD50 for an <i>nramp1</i><sup>−/−</sup> mouse). As expected for this dose, all control mice died during the experiment. However, unlike previously reported, caspase-1<sup>−/−</sup> mice did not show increased resistance to bacterial infection and succumbed to infection more rapidly than the caspase-1<sup>+/+</sup> control animals (Fig. 1 C). These results indicate that in the context of Nramp-1 deficiency, the absence of caspase-1 does not confer resistance to <i>S. typhimurium</i> oral infection, but rather, increases the susceptibility to this pathogen. We also quantified the bacterial loads in the spleens and mesenteric LNs (MLNs) of mice 5 d after oral administration of 10<sup>6</sup> <i>S. typhimurium</i>. Consistent with the previous result, significantly
higher numbers of bacteria were present in the organs of caspase-1−/− mice (P = 0.002 and P < 0.0001 for spleens and MLNs, respectively; Fig. 1 D). Collectively, these results indicate that the absence of caspase-1 in the context of a non-functional nramp1 allele does not result in increased resistance to orally administered S. typhimurium. The observation of higher bacterial loads in systemic tissues of the caspase-1−/−deficient animals indicates that caspase-1 is most likely not required for these bacteria to cross the intestinal barrier as reported previously (8). It is not clear why these results differ from the previous report. It is possible that the different results may be due to the use of a different caspase-1-deficient line because the previous studies were conducted with an independently generated caspase-1−/− mouse in a B10.RIII background. Previous studies have reported that this background exhibits a more pronounced Th1 polarization of the immune response (20). However, more studies will be necessary to determine the bases for the differences in the findings.

To investigate whether the phenotype associated with the absence of caspase-1 could be masked by the absence of a functional nramp1 allele, we crossed the wild-type nramp1 allele into the caspase-1−/− background. The caspase-1−/− genotype of the resulting mice was confirmed by PCR genotyping (not depicted) and by the inability of wild-type S. typhimurium to kill caspase-1−/− BMDMs (Fig. 2 A). The nramp1+/+ status of the mice was confirmed by sequencing (Fig. 2 B). Caspase-1−/−nramp1+/+ mice were then infected orally with 106 wild-type S. typhimurium (~10 LD50 for an nramp1+/+ mouse). As in the case of the nramp1−/− background, the absence of caspase-1 in the context of a wild-type allele of nramp1 also resulted in increased susceptibility to S. typhimurium infection as shown by the shorter time to death (Fig. 2 C). Consistent with these results, bacterial loads recovered from the spleens and MLNs 5 d after infection were significantly higher in caspase-1−/−nramp1+/+ when compared with the controls (P = 0.0016 and P < 0.0001 for spleens and MLNs, respectively; Fig. 2 D). Bacterial loads in mice carrying both mutations (i.e., caspase-1−/−nramp1−/−) were much higher than in mice carrying a mutation in either allele (Fig. 2 D), indicating that Nramp1 and caspase-1 operate in independent defense pathways against S. typhimurium. These experiments demonstrate that the ability of S. typhimurium to kill macrophages in a caspase-1-dependent manner is not required for bacteria to cross the intestinal barrier and become systemic, and that caspase-1 deficiency leads to an increased susceptibility to infection.

Previous studies have shown that the SPI-1 TTSS plays a very important role in the colonization of PPs before its translocation to systemic sites (21, 22). To investigate whether the SPI-1 TTSS− and caspase-1−dependent macrophage death was important for S. typhimurium colonization of PPs, we compared the bacterial loads at this site after infection of wild-type and caspase-1−/− mice. We found that absence of caspase-1 did not decrease but slightly increased (P = 0.114 and P = 0.259 in nramp1−/− and nramp1+/+ backgrounds, respectively) the bacterial loads in PPs in both nramp1−/− and nramp1+/+ backgrounds (Fig. 2 E), further supporting the conclusion that translocation of S. typhimurium to this site does not require the SPI-1 TTSS–mediated macrophage death.

In the mouse, S. typhimurium causes a systemic disease that more closely resembles typhoid fever than gastroenteritis, the syndrome that this bacterium most often causes in humans. However, in mice pretreated with antibiotics, S. typhimurium causes acute colitis, which has been used as a model for the study of S. typhimurium–induced intestinal inflammation (23). Previous studies have demonstrated that the SPI-1–encoded TTSS plays an important role in the ability of S. typhimurium to induce colitis in the streptomycin–treated mouse model (24). However, it is unknown whether the ability of S. typhimurium to rapidly kill macrophages through the activity of its SPI-1–encoded TTSS plays a role in the induction of inflammation in this model system. We therefore compared the ability of S. typhimurium to induce colitis in wild-type and caspase-1−deficient mice because the SPI-1−dependent S. typhimurium–induced macrophage death is dependent on caspase-1. Streptomycin–treated caspase-1−/− and control mice were orally infected with S. typhimurium, and 48 h after infection, ceca were removed for histopathological analysis. Streptomycin–treated uninfected mice exhibited normal histology of the intestinal epithelium (Fig. 3 A). In contrast, streptomycin–treated S. typhimurium–infected caspase-1−/− mice showed marked inflammation of the intestinal epithelium (Fig. 3 A). The cecum histopathology of the infected animals was characterized by profuse mucosal edema, marked infiltration of neutrophils, and substantial disruption of the epithelium. caspase-1−/− mice showed even more pronounced inflammation than control mice (Fig. 3 A). The lesions in the caspase-1−/− mice showed more edema, more neutrophil infiltration, and epithelial disruption. The more pronounced histopathological changes could not be ascribed to higher bacterial burden because there was not a significant difference in the bacterial loads recovered from this tissue in both types of animals (Fig. 3 B). Rather, the more pronounced histopathology may be the result of S. typhimurium reaching deeper tissues in the absence of caspase-1. These results indicate that the ability of S. typhimurium to cause inflammation in the cecum is largely independent of its ability to activate caspase-1. Furthermore, contrary to what has been reported previously (8), the ability of S. typhimurium to rapidly kill macrophages in a SPI-1 TTSS− and caspase-1−dependent manner does not seem to contribute significantly to its ability to cause colitis. Because the SPI-1 TTSS has been shown to be essential for S. typhimurium to cause colitis (24), activities mediated by this TTSS other than macrophage killing must be more important for the stimulation of the inflammatory response.

Caspase-1 is activated upon assembly of an intracellular complex known as the inflammasome. IPAF and NALP3 are key components of this multi-protein complex (2, 25). IPAF is a CARD-containing protein and has been shown to bind the CARD domain of caspase-1 resulting in caspase-1 activation.

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TTSS-dependent caspase-1 activation (13). In contrast, ipaf−/− BMDMs failed to show activation of caspase-1 upon bacterial infection and were as resistant to S. typhimurium–induced death as caspase-1−/− BMDMs (13). These results suggest that IPAF and caspase-1 are in the same pathway of bacterial-induced death. However, ipaf−/− BMDMs did not show any defect in caspase-1 activation when stimulated with pathogen-associated molecular patterns and ATP (13), indicating the existence of alternative pathways of caspase-1 activation. NALP3, another component of the inflammasome, has been implicated in the ASC–dependent activation of caspase-1 (29). However, nalp3−/− BMDMs were fully susceptible to the Salmonella–induced death (30, 31). Collectively, these results suggest the existence of at least two different pathways leading to caspase-1 activation, one mediated by NALP3 and the adaptor molecule ASC (resulting in proinflammatory cytokine production) and the other mediated by IPAF (resulting in cell death). Whether the different outputs are the result of different levels of caspase-1 activation or the result of the recruitment of different caspase-1 effectors is unclear.

Given the observation that S. typhimurium is capable of activating the inflammasome and caspase-1 by different pathways, we examined the role of different components of the inflammasome in S. typhimurium pathogenesis. nalp3+/− and nalp3−/− mice (carrying the nramp1 mutant allele) were infected orally with 10⁶ wild-type S. typhimurium, and survival was monitored daily. Both nalp3+/− and nalp3−/− succumbed to bacterial infection within the same time frame (Fig. 4 A) and exhibited similar bacterial loads in the spleens and MLNs 5 d after infection (Fig. 4 B). We also examined the susceptibility of asc−/− mice to S. typhimurium infection. Similar to nalp3−/− mice, ASC deficiency did not change the susceptibility to S. typhimurium infection as measured by time to death and bacterial loads in different tissues (Fig. 4, C and D). Because the absence of caspase-1 resulted in increased susceptibility to S. typhimurium infection (Figs. 1 and 2), these results suggest that S. typhimurium must be able to activate caspase-1 independently of NALP3 and ASC. Previous studies have also shown that IPAF-deficient macrophages are resistant to S. typhimurium–induced death, suggesting an important role for IPAF in S. typhimurium–induced caspase-1 activation (13). Therefore, we examined the susceptibility of ipaf−/− mice to oral S. typhimurium. ipaf−/− and ipaf−/− mice (carrying the nramp1 mutant allele) were infected orally with 10⁶ S. typhimurium, and the bacterial loads in the spleens and MLNs 5 d after infection were determined. IPAF deficiency did not increase resistance to S. typhimurium infection (Fig. 4 E). In contrast, the bacterial loads were slightly higher in the ipaf−/− mice, although the difference was not statistically significant. The observation that the bacterial loads in systemic tissues were not reduced in the ipaf−/− mice further supports the notion that the IPAF– and caspase-1–dependent Salmonella-induced macrophage death is not required for these bacteria to cross the intestinal barrier.

Collectively, these results, combined with previously published reports (13, 30, 31), indicate that S. typhimurium

(26). NALP3 activates caspase-1 through the adaptor molecule ASC (apoptosis-associated speck-like protein containing a CARD) (27). ASC is essential for the caspase-1 activation mediated by several pathogen-associated molecular patterns (13, 28). Recent studies have also shown that S. typhimurium can kill asc−/− BMDMs, although it does so with delayed kinetics, indicating that ASC is not essential for S. typhimurium

Figure 3. Histopathology of ceca from streptomycin-treated wild-type and caspase-1−/− mice orally infected with S. typhimurium. (A) Wild-type and caspase-1−/− mice (nramp-1+/+ background) were treated with 20 mg streptomycin, and 24 h after antibiotic treatment, mice were either mock infected (control) or infected orally with 10⁶ S. typhimurium. 48 h after infection, ceca were removed, fixed, and embedded in paraffin, and tissue sections were stained with hematoxylin and eosin. Similar results were obtained in three independent animals for each group. (B) Mice were treated and infected with S. typhimurium as indicated above, and bacterial loads in the spleens and ceca were determined 48 h after infection (p-values for the difference between the bacterial loads in the spleens and ceca of caspase-1−/− vs. caspase-1+/+ mice were P = 0.138 and P = 0.483, respectively).
possessed different redundant mechanisms to activate caspase-1 through different components of the inflammasome. Furthermore, these results indicate that contrary to what has been proposed previously, the absence of caspase-1 does not result in resistance to S. typhimurium infection and that this pathogen does not require the activity of this enzyme to cross the intestinal barrier.

**MATERIALS AND METHODS**

**Mouse strains.** The caspase-1−/−, nalp3−/−, and asc−/− mouse lines have been described previously (7, 30) and were backcrossed to the C57BL/6 background for five (caspase-1−/− and nalp3−/−) and six (asc−/−) generations. To generate ipaf−/− mice, an IPAF targeting vector (Fig. S1 A, available at http://www.jem.org/cgi/content/full/jem.20060206/DC1) was electroporated into 129SvEvBrd Lex-1 ES cells. Homologous recombinant ES cells were identified by Southern blot analysis and microinjected into C57BL/6 blastocysts. Chimeric offspring were backcrossed to C57BL/6 mice, and germ-line transmission was confirmed by PCR of tail genomic DNA (Fig. S1 B). Screening of IPAF mice using the primers (no. 28) 5′-GGAGCAGATCTAATCAGAGTCTCAGGAG 3′ and (no. 37) 5′-GAAAGCTCAAACGGCCACGAGC-GCTC 3′ amplify a 744-bp product from the wild-type allele. Primers (no. 37) 5′-GAAGGCCCTACAGGACGACACTC and (Neo3A) 5′-GACGGC-GATCGCTTCTTATC amplify a 222-bp product from the targeted allele. RT-PCR analysis of cDNA isolated from ipaf−/−, ipaf+/−, and ipaf−/− splenocytes (Fig. S1 C) confirmed the absence of IPAF mRNA in ipaf−/− mice. Primers used for RT-PCR analysis were as follows: GAPDH, TCACCCCATGAGAAGGTC and GCTAAGCTGTTGTTGCTCA; IPAF, ATGTACATTATGAGCCCTTGAG and TTGCGACACTCGCTTCAATC. IPAF-deficient mice were backcrossed onto a C57BL/6 background for two generations. All mice were used at 8–12 wk of age. Wild-type littermates were used as controls.

**Nramp1 genotyping.** A 514-bp fragment of the nmrp1 gene was amplified by PCR, using primers 5′-AATGCAATGCTGCGATATGCGC-3′ and 5′-TTTCTCTCCATTAGTATCCCAAG AAG-3′ (forward and reverse, respectively). The purified PCR product was then sequenced using the primer 5′-CCCCCATCTATGTTATCACC-3′.

**S. typhimurium strains.** S. typhimurium SL1344 was the wild-type strain used in all the experiments. SB161 and SL1344 derivative carrying a nonpolar mutation in the invG gene, which encodes an essential component of the SPI-1 TTSS, has been described previously (9). To prepare cultures for cytotoxicity assays or infection of mice, overnight cultures were subcultured for 4 h in LB medium containing 0.3 M NaCl to an OD600 of 0.9 to induce expression of the SPI-1–encoded TTSS.

**Cytotoxicity assays.** BMDMs were seeded on 24-well tissue culture dishes at 2 × 104 cells/well density. Before infection, the complete medium was replaced by serum-free HBSS. Bacteria grown as described above were added to wells at a multiplicity of infection of 20 bacteria/cell, and supernatant samples were collected at the indicated time points to be assayed for lactate dehydrogenase (LDH) activity as a marker for cell death. LDH assays were performed using the CytoTox 96 nonradioactive cytotoxicity assay (Promega).

**Animal infection experiments.** All animal experiments were conducted according to protocols approved by Yale University’s Institutional Animal Care and Use Committee. Groups of age- and sex-matched mice were infected at 8–12 wk of age. After 8 h of fasting, mice were administered by intragastric gavage 100 μl of 10% bicarbonate solution followed by the indicated bacterial dose in 100 μl PBS. To determine bacterial loads in the spleens and MLNs, mice were killed 5 d after infection, organs were homogenized in 3 ml PBS containing 0.05% sodium deoxycholate, and dilutions were plated on LB plates containing streptomycin to determine colony-forming units.

**S. typhimurium–induced colitis model in streptomycin-treated mice.** Bacterial infections in streptomycin-treated animals were performed essentially as described previously (23). In brief, mice (three per group) were treated orally with 20 mg streptomycin, and 24 h after antibiotic treatment, mice were infected orally with wild-type S. typhimurium as described above. Mice were killed 48 h after infection, and ceca were fixed in formalin for histopathology processing. Fixed tissues were embedded in paraffin, and tissue sections were stained with hematoxylin and eosin. In a parallel identical experiment, ceca were homogenized in 3 ml PBS containing 0.05% sodium deoxycholate and dilutions were plated on LB plates containing streptomycin to determine colony-forming units.

**Online supplemental material.** Fig. S1 shows the targeted disruption of the murine IPAF gene and is available at http://www.jem.org/cgi/content/full/jem.20060206/DC1.
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