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FADD and Caspase-8 Mediate Priming and Activation of the Canonical and Noncanonical Nlrp3 Inflammasomes


The Nlrp3 inflammasome is critical for host immunity, but the mechanisms controlling its activation are enigmatic. In this study, we show that loss of FADD or caspase-8 in a RIP3-deficient background, but not RIP3 deficiency alone, hampered transcriptional priming and posttranslational activation of the canonical and noncanonical Nlrp3 inflammasome. Deletion of caspase-8 in the presence or absence of RIP3 inhibited caspase-1 and caspase-11 activation by Nlrp3 stimuli but not the Nlrc4 inflammasome. In addition, FADD deletion prevented caspase-8 maturation, positioning FADD upstream of caspase-8. Consequently, FADD- and caspase-8–deficient mice had impaired IL-1β production when challenged with LPS or infected with the enteropathogen *Citrobacter rodentium*. Thus, our results reveal FADD and caspase-8 as apical mediators of canonical and noncanonical Nlrp3 inflammasome priming and activation. *The Journal of Immunology*, 2014, 192: 000–000.

The Nlrp3 inflammasome responds to a variety of inflammatory triggers, including danger signals (e.g., ATP), microbial toxins (e.g., nigericin), and crystalline substances (1). This inflammasome is also critical for activation of the inflammatory cysteine protease caspase-1 in macrophages infected with enteric pathogens, such as *Vibrio cholerae*, *Escherichia coli*, and *Citrobacter rodentium* (2), and for mounting immune and host responses against *C. rodentium* in vivo (3). Enteropathogen-induced caspase-1 activation and secretion of the inflammasome-dependent cytokines IL-1β and IL-18 are referred to as the “noncanonical” Nlrp3 inflammasome pathway because it also requires caspase-11 for caspase-1 activation (2). Notably, noncanonical Nlrp3 activation in macrophages infected with *Salmonella typhimurium* grown to stationary phase, *E. coli*, or *C. rodentium* recently was shown to require TLR4- and MyD88-mediated Nlrp3 upregulation (4, 5), as well as TLR4/TRIF-mediated induction of caspase-11 expression (5–7). In contrast, caspase-11 is dispensable for canonical Nlrp3 inflammasome activation by danger signals, microbial toxins, and crystalline substances (2).

Engagement of death receptors, such as CD95, TRAIL receptor, and TNFR1, results in recruitment of caspase-8 and its adaptor protein FADD to initiate an apoptosis–inducing caspase cascade (8, 9). Notably, mice deficient for FADD or caspase-8 are embryonic lethal (10–12), and this lethality is rescued by deleting the necrosis-regulating kinase RIP3 (13, 14). These observations suggest that FADD/caspase-8–mediated apoptotic caspase activation and RIP1/RIp3-mediated necroptosis signaling are interconnected at the level of the death-inducing signaling complex. Recent work highlighted a previously unexpected role for caspase-8 in inducing inflammatory responses by promoting IL-1β production under conditions in which canonical inflammasome signaling is prevented (e.g. in caspase-1/11–deficient macrophages) and in response to infectious agents and stimuli that do not engage canonical inflammasome signaling (15–18). In addition, caspase-8 was shown to promote apoptosis induction in response to canonical inflammasome stimuli when the induction of inflammasome-dependent pyroptosis was prevented (19). Together, these studies suggest diverse roles and interconnections between apoptotic and inflammatory signaling pathways. However, the roles of RIP3 and FADD/caspase-8 in regulating canonical and noncanonical Nlrp3 inflammasome signaling in response to stimuli established to trigger activation of the inflammatory caspses-1 and -11 have not been explored. In this study, we revealed caspase-8 and FADD as upstream regulators of Nlrp3 inflammasome signaling in response to stimuli established to trigger activation of the inflammatory caspases-1 and -11 have not been explored. In this study, we revealed caspase-8 and FADD as upstream regulators of Nlrp3 inflammasome signaling, with dual roles in transcriptional priming and posttranslational activation of the canonical and noncanonical Nlrp3 inflammasome pathways, thus shedding light on a new level of interconnection between apoptotic and inflammatory signaling pathways.

Materials and Methods

**Mice**

Rip3<sup>−/−</sup> (20), Rip3<sup>−/−</sup>Casp8<sup>−/−</sup> (14), Rip3<sup>−/−</sup>Fadd<sup>−/−</sup> (21), Nlrp3<sup>−/−</sup> (22), Asc<sup>−/−</sup> (23), Casp1<sup>−/−</sup>Casp11<sup>−/−</sup>, Casp1<sup>−/−</sup>Casp11<sup>−/−</sup> (2) , IFNAR2<sup>−/−</sup> (24), Trif<sup>−/−</sup> (25), Trif<sup>−/−</sup> (26), MyD88<sup>−/−</sup> (27), Nod2<sup>−/−</sup> (28).

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Abbreviations used in this article: BMDM, bone marrow–derived macrophage; MDP, muramyl dipeptide; moI, multiplicity of infection; WT, wild-type.

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2 CASPASE-8/FADD IN NLRP3 INFLAMMASOME ACTIVATION

(28), TNF-α−/− (29), and TNFRI−/− (30) mice were described previously. Caspase-8+/− mice were bred with Ly5M−/− (B6.129P2-Ly5m+/-Scid/J; The Jackson Laboratory) mice to generate conditional caspase-8-knockout mice. C57BL/6 wild-type (WT; The Jackson Laboratory), Rip3+/− Casp8−/−, and Rip3−/− Fadd−/− mice and littermate controls were bred at St. Jude Children’s Research Hospital. Animal studies were conducted under protocols approved by St. Jude Children’s Research Hospital’s and Ghent University’s Committee on the Use and Care of Animals.

Macrophenage differentiation and stimulation

Bone marrow–derived macrophages (BMDMs) were prepared as described previously (5). In brief, bone marrow cells were grown in L–conditioned IMDM supplemented with 10% FBS, 1% nonessential amino acid, and 1% penicillin-streptomycin for 5 d to differentiate into macrophages. On day 5, BMDMs were seeded in six-well cell culture plates and were stimulated the next day with LPS (20 ng/ml) for 4 h, the last 30 min of which was in the presence of 5 mM ATP or 20 μM nigericin. Where indicated, BMDMs were treated with the caspase-8 inhibitor Ac-IETD-fmk (Calbiochem; 20 μM) before or after LPS priming, respectively. In other experiments, BMDMs that were pretreated or not with LPS were infected with C. rodentium or E. coli at a multiplicity of infection (moi) 25 for 24 h. Two hours postinfection, gentamycin (100 μg/ml) was added to the culture medium.

In vitro transcription/translation

35S-labeled procaspases were produced in vitro using the SP6 High-Yield Wheat Germ Protein Expression System (Promega) and incubated with 100 U recombinant mouse caspase-8 (Enzo Life Sciences) or 35 ng mouse caspase-3 (Flinders Institute for Biotechnology) before caspase processing was analyzed by autoradiography.

Western blotting

Samples for immunoblotting were prepared by combining cell lysates with culture supernatants. Samples were denatured in loading buffer containing SDS and 100 mM DTT and boiled for 5 min. SDS-PAGE–separated proteins were transferred to polyvinylidene difluoride membranes and immunoblotted with primary Abs against caspase-1 (Adipogen; AG-20B-0042), pro-caspase-8 (Enzo Life Sciences; 1G12), cleaved caspase-8 (Cell Signaling Technology; D5B2), caspase-11 (Novus Biologicals; 17D9), FADD (Millipore; 1F7), Nlrp3 (Adipogen; AG-20B-0014), IL-1β (Cell Signaling Technology; D5B2), and IL-18 (Cell Signaling Technology; D10H11), followed by secondary anti-rabbit, anti-rat, anti-mouse, or anti-goat HRP Abs (Jackson ImmunoResearch Laboratories), as previously described (22).

Flow cytometry and phagocytosis assay

BMDMs were stained with CD11b, F4/80, and CD86 Abs (eBioscience) or were preincubated with GFP-expressing C. rodentium, FITC-labeled zymosan A, or OVA (Molecular Probes) for 3 h prior to analysis on an LSR II (BD Biosciences) using FlowJo software.

Confocal immunofluorescence microscopy

WT, Casp1−/−, and Rip3−/− Casp8−/− macrophages grown on coverslips were left untreated (control), stimulated with LPS+ATP, or infected with C. rodentium. Cells were fixed with 4% paraformaldehyde and stained with caspase-1 (Adipogen) or caspase-8 (Cell Signaling Technology) Abs. Nuclei were counterstained with DAPI. Cells were mounted on glass slides using ProLong Gold Antifade Reagent (Life Technologies), and micrographs were taken with a Nikon C1 confocal microscope using a 40× objective lens. The images were processed and analyzed with ImageJ software. The images were taken at Cell and Tissue Imaging Center Light Microscopy Facility at St. Jude Children’s Research Hospital.

LPS-induced endotoxemia and in vivo C. rodentium infection

In some experiments, cohorts of WT, Rip3−/−, Rip3−/− Casp8−/−, and Rip3+− Fadd−/− mice were infected i.p. with 35 mg/kg LPS (Sigma-Aldrich) for 5 h before serum was collected for cytokine analysis. In other experiments, groups of WT, Rip3−/−, Rip3−/− Casp8−/−, and Rip3−/− Fadd−/− mice were infected with C. rodentium (ATCC 51459; 1 × 106 CFU) by oral gavage. Food and water intake were stopped 8 h prior to infection and allowed to resume 1 h after infection. To determine bacterial counts, serial dilutions of homogenized feces were plated on MacConkey agar plates and incubated at 37°C for 24 h. Stool consistency was scored (stool score) according to standard protocol, as described previously (3). Briefly, 1 = soft pellet, 2 = semi-formed pellet, and 3 = not adherent to the anus, 4 = liquid stool that adhere to the anus, and 5 = liquid stool with blood.

Cytokine analysis

Concentrations of cytokines and chemokines were determined by multiplex ELISA (Millipore) or classical ELISA for IL-1β (eBioscience) or IL-18 (MBL International).

Real-time PCR

Total RNA was extracted from cells stimulated with LPS or infected with C. rodentium using TRIzol reagent (Life Technologies), according to the manufacturer’s instructions. RNA was quantified, and 1 μg total RNA was reverse transcribed to complementary DNA with poly(dT) primers using the First-Strand CDNA Synthesis Kit (Life Technologies). Transcript levels of pro-IL-1β and Nlrp3 were quantified by quantitative RT-PCR on an ABI 7500 real-time PCR instrument with SYBR Green (Applied Biosystems). Gapdh expression was used for normalization, and results are presented as fold induction over levels in untreated control cells.

Statistics

GraphPad Prism 5.0 software was used for data analysis. Data are presented as mean ± SEM. Statistical significance was determined by the Student t test; p < 0.05 was considered statistically significant.

Results

FADD is critical for potent canonical and noncanonical Nlrp3 inflammasome activation

Conditional deletion of FADD in hematopoietic progenitor cells affects myeloid cell differentiation into BMDMs (32). However, simultaneous deletion of RIP3 and FADD did not cause global defects in macrophage differentiation, because Rip3−/− Fadd−/− macrophages lacked morphologically normal and expressed normal levels of the myeloid cell/macrophage surface markers CD11b, F4/80, and CD86 (Supplemental Fig. 1A–D), indicating that Rip3−/− Fadd−/− macrophages were not functionally impaired. To understand the roles of RIP3 and FADD in canonical Nlrp3 inflammasome activation, LPS–primed WT, Rip3−/−, and Rip3−/− Fadd−/− macrophages were stimulated with ATP or nigericin, and caspase-1 processing was monitored. Under these conditions, ATP- and nigericin-induced caspase-1 activation was significantly blunted in LPS–primed macrophages that lacked FADD in a RIP3-deficient background but not in cells lacking RIP3 only (Fig. 1A). ATP-induced caspase-1 processing was also reduced significantly in Pam3CSK4–primed Rip3−/− Fadd−/− macrophages (Fig. 1B), indicating that the requirement for FADD was not restricted to TLR4–stimulated cells. In addition to these canonical Nlrp3 stimuli, FADD deficiency hampered noncanonical Nlrp3 inflammasome activation in macrophages infected with the enteropathogens C. rodentium and E. coli; cells lacking RIP3 and FADD were defective in procaspase-1 maturation, whereas WT and Rip3−/− macrophages responded to these enteropathogens with robust activation of caspase-1 (Fig. 1C). Because caspase-11 is required for caspase-1 maturation in enteropathogen-infected macrophages (2), defective caspase-1 maturation in Rip3−/− Fadd−/− macrophages may be consequent to their inability to activate caspase-11. Indeed, C. rodentium– and E. coli–infected Rip3−/− Fadd−/− macrophages also were blunted in maturation of procaspase-11 into the large catalytic subunit (p30) (Fig. 1C). In addition, they failed to secrete significant amounts of IL-18 (Fig. 1D) or IL-1β (Fig. 1E) in the culture medium. The roles of RIP3 and FADD in enteropathogen–induced Nlrp3 inflammasome activation are specific, because RIP3 and FADD were dispensable for S. typhimurium–induced caspase-1 activation (Fig. 1F), which proceeds through the
Nlrc4 inflammasome (23). Together, these results suggest a specific role for FADD in potent activation of the canonical and noncanonical arms of the Nlpr3 inflammasome.

**FADD mediates caspase-8 maturation with canonical and noncanonical Nlpr3 inflammasome stimuli**

FADD modulates apoptosis and necroptosis signaling through its associated effector protease caspase-8 (21). Therefore, we analyzed the expression and activation status of caspase-8 under conditions well-known to elicit activation of the canonical and noncanonical Nlpr3 inflammasomes. WT, RIP3-deficient, and Rip3<sup>−/−</sup>Fadd<sup>−/−</sup> cells expressed comparable levels of procaspase-8, but procaspase-8 processing into the large catalytic (p17) subunit was markedly reduced in LPS-primed Rip3<sup>−/−</sup>Fadd<sup>−/−</sup> macrophages that were treated with the canonical Nlpr3 inflammasome stimuli ATP and nigericin (Fig. 2A). Notably, combined stimulation with LPS and ATP was needed to induce caspase-8 maturation, because WT, RIP3-deficient, and Rip3<sup>−/−</sup>Fadd<sup>−/−</sup> macrophages that were treated with only LPS or ATP failed to process caspase-8 (Supplemental Fig. 2A). Silica-treated macrophages also required FADD for potent

**FIGURE 1.** FADD is required for canonical and noncanonical Nlpr3 inflammasome activation. WT, Rip3<sup>−/−</sup>, and Rip3<sup>−/−</sup>Fadd<sup>−/−</sup> BMDMs were primed with 20 ng/ml LPS (A) or 2.5 μg/ml PAM3CSK4 (B) for 4 h, the last 30 min of which was in the presence 5 mM ATP or 20 μM nigericin. Lysates were immunoblotted for caspase-1. WT, Rip3<sup>−/−</sup>, and Rip3<sup>−/−</sup>Fadd<sup>−/−</sup> BMDMs were infected with C. rodentium or E. coli (moi 25) for 24 h before lysates were collected and immunoblotted for the indicated proteins (C), and culture supernatants were analyzed for secreted IL-1β (D) and IL-18 (E). (F) WT, Rip3<sup>−/−</sup>, and Rip3<sup>−/−</sup>Fadd<sup>−/−</sup> BMDMs were infected with S. typhimurium (moi 5) for 4 h before cell lysates were immunoblotted for caspase-1. ELISA data are shown as mean ± SEM, and all data are representative of at least three independent experiments.
induction of caspase-1 maturation and caspase-8 processing (Supplemental Fig. 2B). In addition, caspase-8 activation was reduced significantly in C. rodentium– and E. coli–infected Rip3<sup>−/−</sup> Fadd<sup>−/−</sup> cells but not in Rip3<sup>−/−</sup> macrophages (Fig. 2B). Together, these results suggest that caspase-8 is processed under inflammasome-activating conditions. To further understand the relationship between FADD-induced caspase-8 maturation and Nlrp3 inflammasome activation, we monitored caspase-8 activation status in inflammasome-deficient macrophages. As reported for LPS+nigericin-treated macrophages (19), neither loss of caspase-11 nor combined loss of caspase-1 and -11 affected caspase-8 activation in LPS+ATP-stimulated cells, whereas loss of Nlrp3 or ASC inhibited LPS+ATP-induced caspase-8 processing (Fig. 2C). As reported (2), C. rodentium– and E. coli–induced caspase-1 processing was abolished in Nlrp3<sup>−/−</sup>, Asc<sup>−/−</sup>, Casp1<sup>−/−</sup>Casp11<sup>Tg</sup>, Casp11<sup>−/−</sup>, and Casp1<sup>−/−</sup>Casp11<sup>Tg</sup> macrophages in which caspase-11 expression was restored from a C57BL/6 bacterial artificial chromosome (Casp1<sup>−/−</sup>Casp11<sup>Tg</sup>) (Fig. 2D). Caspase-11 expression and maturation were not affected in these macrophages.

**FIGURE 2.** FADD is required for caspase-8 maturation in response to canonical and noncanonical Nlrp3 stimuli. (A) WT, Rip3<sup>−/−</sup>, and Rip3<sup>−/−</sup>Fadd<sup>−/−</sup> BMDMs were stimulated with 20 ng/ml LPS for 4 h, the last 30 min of which was in the presence 5 mM ATP or 20 μM nigericin. Cell lysates were immunoblotted for the indicated proteins. (B) WT, Rip3<sup>−/−</sup>, and Rip3<sup>−/−</sup>Fadd<sup>−/−</sup> BMDMs were infected with C. rodentium or E. coli (moi 25) for 24 h before lysates were collected and immunoblotted for the indicated proteins. (C–G) WT, Tlr4<sup>−/−</sup>, Trif<sup>−/−</sup>, MyD88<sup>−/−</sup>, IFNAR<sup>−/−</sup>, Nlrp3<sup>−/−</sup>, Asc<sup>−/−</sup>, Casp1<sup>−/−</sup>Casp11<sup>Tg</sup>, Casp11<sup>−/−</sup>, and Casp1<sup>−/−</sup>Casp11<sup>Tg</sup> BMDMs were stimulated with LPS+ATP or infected with C. rodentium and E. coli, as above, before cell lysates were immunoblotted for the indicated proteins. All data are representative of at least three independent experiments.
The potential role of caspase-8 in canonical and noncanonical Nlrp3 inflammasome, we next sought genetic confirmation of Having established a role for FADD in activation of caspase-8 and inflammasome activation Caspase-8/RIP3 deletion inhibited canonical Nlrp3 inflammasome activation. (Supplemental Fig. 2D, 2E), suggesting that caspase-8-deficient mice contained cells in which deletion of the floxed Casp8LysM-Cre allele (33). As reported for an independently generated Casp8LysM-Cre+ mice mainly contained cells in which deletion of the floxed caspase-8 allele had failed to occur (Supplemental Fig. 2D, 2E). In contrast, caspase-8 was successfully deleted in Rip3−/−Casp8−/− BMDMs (Supplemental Fig. 2D, 2E), suggesting that caspase-8-deficient myeloid progenitor cells might be sensitive to RIP3-mediated necroptosis. To characterize Rip3−/−Casp8−/− BMDMs phenotypically, we confirmed that they appeared morphologically normal; that they expressed normal levels of the monocyte/macrophage markers CD11b, F4/80, and CD86 (Supplemental Fig. 1A–D); and that phagocytosis of pathogenic bacteria, fungal cell wall components, and antigenic peptides was not impaired (Supplemental Fig. 1E–G). In line with the hypothesized role for caspase-8 in mediating efficient canonical Nlrp3 inflammasome activation, ATP- and nigericin-induced caspase-8 maturation were not in macrophages lacking RIP3 alone (Fig. 4A). In contrast, caspase-11 processing was normal in enteropathogen-infected macrophages lacking RIP3 alone (Fig. 4A, Supplemental Fig. 4A). FADD and caspase-8 mediate cellular responses to TNF-α (36); however, their role in ATP-induced Nlrp3 inflammasome activation was independent of TNF-α signaling, because TNF-α−/− and TNF-R1−/− BMDMs responded to LPS+ATP stimulation with normal caspase-1 and caspase-8 activation, and they secreted normal levels of IL-1β (Supplemental Fig. 3A–C). Together, these results demonstrate that Rip3−/−Casp8−/− macrophages are significantly impaired in canonical Nlrp3 inflammasome activation.

Enteropathogen-induced Nlrp3 activation is impaired in Rip3/caspase-8−/−knockout macrophages
To explore the role of caspase-8 in noncanonical Nlrp3 inflammasome signaling, macrophages were infected with the enteropathogens C. rodentium and E. coli. Notably, caspase-1 maturation was significantly impaired in C. rodentium− and E. coli−infected Rip3−/−Casp8−/− macrophages (Fig. 4A, Supplemental Fig. 4A). In contrast, caspase-1 processing was normal in enteropathogen-infected macrophages lacking RIP3 alone (Fig. 4A). As was recently reported (37), caspase-1 maturation was also not affected in S. typhimurium−infected Rip3−/−Casp8−/− cells (Fig. 4B), demonstrating specificity of these results. As with canonical Nlrp3 inflammasome stimuli, TNF-α signaling also was dispensable for enteropathogen-induced caspase-1 and caspase-8 activation in macrophages infected with C. rodentium (Supplemental Fig. 3F). Analysis of caspase-11 processing in C. rodentium− and E. coli−infected Rip3−/−Casp8−/− macrophages further supported an upstream role for caspase-8 in mediating noncanonical Nlrp3 inflammasome activation, because caspase-11 maturation was specifically affected in Rip3−/−Casp8−/− BMDMs (Fig. 4C). Concurrently, the time-dependent secretion of IL-1β (Fig. 4D) and the induction of IL-1α release and pyroptosis (Fig. 4E, 4F) were specifically reduced in C. rodentium−infected Rip3−/−Casp8−/− macrophages but not in macrophages lacking only RIP3. Together, these results show that enteropathogen-induced activation of caspase-11 and the noncanonical Nlrp3 inflammasome are hampered severely in Rip3−/−Casp8−/− macrophages.

Caspase-8 and FADD mediate transcriptional priming of the Nlrp3 inflammasome
Nlrp3 inflammasome activation is a highly regulated process at both the transcriptional and posttranslational levels. At the transcriptional level, Nlrp3 inflammasome-mediated caspase-1 activation and IL-1β secretion require TLR4/MyD88-mediated upregulation of Nlrp3 and proIL-1β expression (4, 5). In addition, C. rodentium− and E. coli−induced Nlrp3 inflammasome activation requires TLR4/TRIF-mediated expression of caspase-11 (5–7). To further determine the level at which FADD and caspase-8

Caspase-8/RIP3 deletion inhibits canonical Nlrp3 inflammasome activation
Having established a role for FADD in activation of caspase-8 and inflammasome activation Caspase-8/RIP3 deletion inhibited canonical Nlrp3 inflammasome activation. (Supplemental Fig. 2D, 2E). However, both LPS+ATP- and C. rodentium−induced caspase-8 maturation were markedly reduced in TLR4− and TRIF−deficient macrophages (Fig. 2E, 2F). Moreover, caspase-8 processing was reduced in MyD88−/− macrophages (Fig. 2E and 2F), suggesting that, in addition to FADD, caspase-8 activation further required TLR-dependent signaling. Notably, C. rodentium− and E. coli−induced caspase-8 activation was partially affected in IFNAR1−/− macrophages (Fig. 2G), suggesting that type 1 IFN signaling contributes to efficient caspase-8 activation in enteropathogen-infected macrophages. Together, these results implicate TLR and type 1 IFN signaling in caspase-8 activation by stimuli of the canonical and noncanonical Nlrp3 inflammasome, respectively. In addition, our observations that caspase-8 activation is defective in Rip3−/−Fadd−/− cells and that Nlrp3 and ASC mediate caspase-8 maturation in response to canonical Nlrp3 stimuli suggest that caspase-8 may operate downstream of FADD in regulating Nlrp3 inflammasome responses.

Caspase-8/RIP3 deletion inhibits canonical Nlrp3 inflammasome activation
Having established a role for FADD in activation of caspase-8 and the Nlrp3 inflammasome, we next sought genetic confirmation of the potential role of caspase-8 in canonical and noncanonical Nlrp3 inflammasome activation. To this end, we differentiated BMDMs from caspase-8−deficient mice in a RIP3−/− background (14), as well as from animals with a conditionally targeted deletion of caspase-8 in myeloid progenitor cells (Casp8LysM-Cre) (33). As reported for an independently generated Casp8LysM-Cre+ mouse line (34), BMDM cultures of Casp8LysM-Cre+ mice mainly contained cells in which deletion of the floxed caspase-8 allele had failed to occur (Supplemental Fig. 2D, 2E). In contrast, caspase-8 was successfully deleted in Rip3−/−Casp8−/− BMDMs (Supplemental Fig. 2D, 2E), suggesting that caspase-8−deficient myeloid progenitor cells might be sensitive to RIP3-mediated necroptosis. To characterize Rip3−/−Casp8−/− BMDMs phenotypically, we confirmed that they appeared morphologically normal; that they expressed normal levels of the monocyte/macrophage markers CD11b, F4/80, and CD86 (Supplemental Fig. 1A–D); and that phagocytosis of pathogenic bacteria, fungal cell wall components, and antigenic peptides was not impaired (Supplemental Fig. 1E–G). In line with the hypothesized role for caspase-8 in mediating efficient canonical Nlrp3 inflammasome activation, ATP- and nigericin-induced caspase-8 maturation were affected significantly in LPS-primed Rip3−/−Casp8−/− macrophages but not in macrophages lacking RIP3 alone (Fig. 3A). ATP-induced maturation of caspases-1 and -8 already was evident in WT and Rip3−/− macrophages 5 min after ATP exposure, and it increased further with similar kinetics in these cells (Fig. 3B). In addition to inducing rapid caspase-1 maturation, potent canonical Nlrp3 inflammasome stimulation induces rapid pyroptotic cell death, whereas induction of caspase-8−dependent apoptosis proceeds with slower kinetics and prevails in caspase-1−deficient macrophages (19, 35). Accordingly, we noted that both ATP-induced pyroptosis (Fig. 3C) and IL-1β secretion (Fig. 3D) followed suit and already were evident 10 min after ATP exposure. Consistent with an upstream requirement for FADD and caspase-8 in potentiating caspase-1 activation (Figs. 1A, 3B), the time-dependent induction of pyroptosis and IL-1β secretion were specifically reduced in LPS+ATP-treated Rip3−/−Fadd−/− and Rip3−/−Casp8−/− macrophages (Fig. 3C, 3D). Rip3−/−Casp8−/− macrophages were similarly defective in ATP-induced caspase-1 processing and IL-1β secretion after priming with the TLR2 ligand Pam3CSK4 (Fig. 3E, 3F), demonstrating that the role of caspase-8 in Nlrp3 inflammasome activation was not limited to LPS-primed macrophages. Both FADD and caspase-8 mediate cellular responses to TNF-α (36); however, their role in ATP-induced Nlrp3 inflammasome activation was independent of TNF-α signaling, because TNF-α−/− and TNF-R1−/− BMDMs responded to LPS+ATP stimulation with normal caspase-1 and caspase-8 activation, and they secreted normal levels of IL-1β (Supplemental Fig. 3A–C). Together, these results demonstrate that Rip3−/−Casp8−/− macrophages are significantly impaired in canonical Nlrp3 inflammasome activation.
regulated Nlrp3 inflammasome activation, we analyzed Nlrp3 and proIL-1β expression levels in LPS-primed macrophages. Notably, LPS-induced upregulation of Nlrp3 mRNA (Fig. 5A) and protein expression (Fig. 5B) levels were reduced significantly in Rip3<sup>−/−</sup> Fadd<sup>−/−</sup> macrophages. In agreement with FADD being responsible for these effects, loss of RIP3 alone did not significantly affect Nlrp3 expression (Fig. 5A, 5B). Concurrently, Rip3<sup>−/−</sup> Fadd<sup>−/−</sup> macrophages were defective in LPS-induced proIL-1β mRNA (Fig. 5C), as well as in LPS-induced protein expression (Supplemental Fig. 2A) and LPS+silica-induced proIL-1β maturation (Fig. 5D, Supplemental Fig. 4B), suggesting that FADD regulated TLR4/NF-κB–dependent transcriptional priming of the Nlrp3 inflammasome. Indeed, LPS-induced phosphorylation of IKBα and ERK was specifically reduced in Rip3<sup>−/−</sup> Fadd<sup>−/−</sup> macrophages but not in cells lacking RIP3 only (Fig. 5E). In agreement, LPS-induced secretion of the NF-κB–dependent cytokines IL-6 (Fig. 5F) and KC (Fig. 5G) was reduced significantly in the absence of FADD. In line with caspase-8 operating downstream of FADD, proIL-1β mRNA (Fig. 5H) and protein expression (Supplemental Fig. 2A) also were downregulated significantly in LPS-primed Rip3<sup>−/−</sup> Casp8<sup>−/−</sup> macrophages. As a result, levels of both proIL-1β and mature IL-1β were significantly reduced in LPS+ATP- and LPS+silica-treated Rip3<sup>−/−</sup> Casp8<sup>−/−</sup> macrophages (Fig. 5I, Supplemental Fig. 4B). To address whether FADD and caspase-8 were specifically involved in TLR-induced NF-κB activation, we stimulated cells with the NOD2 agonist muramyl dipeptide (MDP). As expected, NOD2-deficient macrophages failed to induce proIL-1β mRNA levels in response to MDP (Fig. 5J). Notably, Rip3<sup>−/−</sup> Fadd<sup>−/−</sup> and Rip3<sup>−/−</sup> Casp8<sup>−/−</sup> macrophages also were significantly affected in their ability to upregulate proIL-1β mRNA levels in response to MDP, albeit not to the extent of Nod2<sup>−/−</sup> macrophages (Fig. 5J). Together, these results demonstrate an accessory role for FADD and caspase-8 in NF-κB–dependent transcriptional upregulation of Nlrp3 and proIL-1β in cells primed with TLR and non-TLR agonists.

**Role of caspase-8 in posttranslational activation of the Nlrp3 inflammasome**

We next addressed whether caspase-8 also regulated Nlrp3 inflammasome activation at the posttranslational level. To formally explore this, WT macrophages were treated with the pharma-
The caspase-8 inhibitor Ac-IETD-fmk prior to or after LPS priming. As expected, both proIL-1β expression and secretion of mature IL-1β (Fig. 6A, 6B) were significantly induced in macrophages treated with LPS and ATP in the absence of the caspase-8 inhibitor. In line with our genetic evidence that caspase-8 mediated LPS-induced production of proIL-1β (Fig. 5H, Supplemental Fig. 2A), macrophages incubated with the caspase-8 inhibitor prior to being exposed to LPS had reduced levels of proIL-1β expression relative to cells that were primed with LPS before incubation with the inhibitor (Fig. 6A). In agreement with caspase-8 regulating canonical Nlrp3 inflammasome activation posttranscriptionally, the caspase-8 inhibitor Ac-IETD-fmk markedly reduced ATP-induced proIL-1β maturation (Fig. 6A) and secretion of mature IL-1β (Fig. 6B) in these cells. Unlike proIL-1β, proIL-18 is constitutively expressed in macrophages, and its levels were not reduced in cells receiving Ac-IETD-fmk prior to LPS (Fig. 6A). Nevertheless, IL-18 secretion in the culture medium also was hampered severely in macrophages treated with Ac-IETD-fmk prior to ATP stimulation (Fig. 6C). In agreement with caspase-8 regulating Nlrp3 inflammasome activation at the posttranslational level, the caspase-8 inhibitor prevented caspase-1 and caspase-8 maturation, regardless of whether it was provided before or after LPS priming (Fig. 6D). In contrast, Ac-IETD-fmk failed to inhibit S. typhimurium–induced caspase-1 maturation (Fig. 6E), demonstrating that it did not target caspase-1 enzymatic activity directly. Our observation that Nlrp3 and ASC were required for LPS+ATP–induced caspase-8 maturation (Fig. 2C) suggests that caspase-8 interacts with inflammasome components. Thus, we hypothesized that caspase-8 may induce canonical Nlrp3 inflammasome activation by directly processing procaspase-1. Indeed, recombinant caspase-8 potently matured procaspase-1 into p30, p20, and p10 subunits associated with active caspase-1 (Fig. 6F). Such a role for caspase-8 appeared to be specific, because recombinant caspase-3 failed to cleave procaspase-1 under conditions that allowed it to efficiently process the caspase-3 and -7 zymogens (Supplemental Fig. 4C, 4D). To further address whether endogenous caspase-8 mediated caspase-1 activation by the canonical Nlrp3 inflammasome, lysates of untreated and LPS+ATP-stimulated WT, Rip32/2, and Rip32/2Casp82/2 BMDMs were infected with C. rodentium (moi 25) for 4, 8, or 16 h before culture supernatants were analyzed for IL-1β (D), IL-1α (E), and LDH (F). Data are mean ± SEM, and all results are representative of at least three independent experiments. *p < 0.05, **p < 0.01.
mote caspase-1 activation through both cleavage and proximity-induced autoactivation of procaspase-1 in the Nlrp3 inflammasome. In agreement, confocal immunofluorescence analysis showed significant colocalization of caspase-1 and caspase-8 in macrophages that were stimulated with LPS+ATP or infected with C. rodentium but not in untreated cells (Fig. 6H). This observation

FIGURE 5. FADD and caspase-8 mediate transcriptional priming of the Nlrp3 inflammasome. WT, Rip3<sup>−/−</sup>, and Rip3<sup>−/−</sup> Fadd<sup>−/−</sup> BMDMs were left untreated or stimulated with 20 ng LPS for 2 or 4 h. Induction of Nlrp3 (A) and proIL-1β (C) mRNA was determined as described in Materials and Methods. (B and D) WT, Rip3<sup>−/−</sup>, and Rip3<sup>−/−</sup> Fadd<sup>−/−</sup> BMDMs were stimulated with 20 ng LPS for 4 h, the last 30 min of which was in the presence of 5 mM ATP or 20 μM nigericin. Lysates were immunoblotted for Nlrp3 (B) and IL-1β (D). (E) WT, Rip3<sup>−/−</sup>, and Rip3<sup>−/−</sup> Fadd<sup>−/−</sup> BMDMs were stimulated with LPS for the indicated durations. Lysates were immunoblotted for total and phosphorylated IκBα and ERK. WT, Rip3<sup>−/−</sup>, and Rip3<sup>−/−</sup> Fadd<sup>−/−</sup> BMDMs were stimulated with 20 ng/ml LPS for 4 h, and the levels of secreted IL-6 (F) and KC (G) in culture supernatants were determined by multiplex ELISA. (H) WT, Rip3<sup>−/−</sup>, and Rip3<sup>−/−</sup> Casp8<sup>−/−</sup> BMDMs were stimulated with 20 ng LPS for 0, 2, or 4 h before proIL-1B mRNA levels were determined, as described in Materials and Methods. (I) WT, Rip3<sup>−/−</sup>, and Rip3<sup>−/−</sup> Casp8<sup>−/−</sup> BMDMs were stimulated with LPS+ATP, as described above, before combined cell lysates and culture supernatants were immunoblotted for IL-1β. (J) WT, Rip3<sup>−/−</sup>, Rip3<sup>−/−</sup> Casp8<sup>−/−</sup>, and Rip3<sup>−/−</sup> Fadd<sup>−/−</sup> BMDMs were stimulated with 10 μg MDP for the indicated durations before proIL-1B mRNA levels were determined, as described in Materials and Methods. ELISA data are shown as mean ± SEM, and all data are representative of three independent experiments. *p < 0.05.
is in line with a recent report (19) demonstrating significant colocalization of caspase-8 and ASC in confocal micrographs of LPS+nigericin-treated Casp1<sup>−−</sup>Casp11<sup>−−</sup> macrophages. Together, our results suggest that FADD and caspase-8 interact with core components of the Nlrp3 inflammasome and promote activation of procaspase-1 in the complex.

FIGURE 6. Caspase-8 is required for posttranslational activation of the Nlrp3 inflammasome. (A–D) WT BMDMs were stimulated with 20 ng LPS for 4 h, the last 30 min of which was in the presence of 5 mM ATP or 20 μM nigericin. In some setups, the caspase-8 inhibitor Ac-IETD-fmk (20μM) was added 10 min prior to LPS treatment, whereas in other setups it was added 10 min prior to ATP treatment. Lysates were immunoblotted for the indicated proteins (A, D), and cell supernatants were analyzed for secreted IL-1β (B) and IL-18 (C). (E) WT BMDMs were pretreated with vehicle control (DMSO) or 20 μM caspase-8 inhibitor Ac-IETD-fmk before being infected with S. typhimurium (moi 5) for 4 h. Lysates were immunoblotted for caspase-1. (F) 35S-labeled procaspase-1 was produced in vitro and incubated with recombinant caspase-8 (100 U) at 37˚C for 1 h before caspase-1 processing was analyzed by autoradiography. In some setups, caspase-8 was incubated with 1 μM zV AD-fmk prior to coincubation with procaspase-1. (G) WT, Rip3<sup>−−</sup>, and Rip3<sup>−−</sup>Casp8<sup>−−</sup> BMDMs were stimulated with LPS and ATP as above, and cell lysates prepared by freeze-thawing in liquid N<sub>2</sub> were immunoblotted for caspase-1. Samples containing 1 mg protein were incubated in the presence or absence of 10 μM biotin-V AD-fmk (Enzo Life Sciences) for 45 min, followed by precipitation with streptavidin-agarose (Thermo Scientific) at 4˚C overnight before immunoblotting for caspase-1. Asterisk indicates nonspecific immunoreactive bands of the respective Abs. (H) BMDMs grown on coverslips were stimulated with LPS+ATP or infected with C. rodentium, as above. Cells were fixed and immunostained for caspase-1 (green) and caspase-8 (red). DAPI was used for nuclear staining. Scale bars, 10 μm. Data are representative of three independent experiments. *p < 0.05.
In vivo role of FADD and caspase-8 in Nlrp3 inflammasome activation

To demonstrate the in vivo relevance of FADD and caspase-8 in Nlrp3 inflammasome signaling, cohorts of WT, Rip3$^{-/-}$, Rip3$^{-/-}$Casp8$^{-/-}$, and Rip3$^{-/-}$Fadd$^{-/-}$ mice were challenged with a lethal dose of LPS. The LPS-induced endotoxemia model was selected because both caspase-1 (2) and caspase-11 (2, 38) are required for IL-1$\beta$ production in LPS-challenged mice, whereas circulating IL-1$\alpha$ levels are regulated by caspase-11 independently of caspase-1 (2). Notably, circulating levels of both IL-1$\beta$ (Fig. 7A) and IL-1$\alpha$ (Fig. 7B) were reduced significantly in LPS-challenged Rip3$^{-/-}$Casp8$^{-/-}$ and Rip3$^{-/-}$Fadd$^{-/-}$ mice relative to those of LPS-treated WT and Rip3$^{-/-}$ mice, thus extending the roles of FADD and caspase-8 in Nlrp3 inflammasome signaling to a relevant in vivo setting. The Nlrp3 inflammasome also plays a critical role in controlling C. rodentium replication in vivo (3). As in Nlrp3$^{-/-}$ and Casp1$^{-/-}$/Casp11$^{-/-}$ mice (3), bacterial burdens (Fig. 7C) and stool scores (Fig. 7D) were significantly elevated in C. rodentium–infected Rip3$^{-/-}$Casp8$^{-/-}$ and Rip3$^{-/-}$Fadd$^{-/-}$ mice relative to those of infected WT and Rip3$^{-/-}$ mice.

**FIGURE 7.** In vivo role of caspase-8 and FADD in inflammasome responses during LPS-induced endotoxemia and C. rodentium infection. Mice of the indicated genotypes were injected with 35 mg/kg LPS for 5 h before serum was collected and analyzed for IL-1$\beta$ (A) and IL-1$\alpha$ (B). Mice of the indicated genotypes were infected orally with C. rodentium, and titers in feces (C) and stool consistency (D) were examined on day 15 postinfection. Each symbol represents a mouse. Data are mean ± SEM. (E) Schematic representation of the roles of FADD and caspase-8 in canonical and noncanonical Nlrp3 inflammasome signaling. LPS-induced TLR4 activation triggers MyD88-dependent upregulation of NLRP3 and proIL-1$\beta$ levels, as well as TRIF-dependent procaspase-11 induction to prime the canonical and noncanonical Nlrp3 inflammasomes for activation by their respective ligands and bacterial pathogens. FADD and caspase-8 are required for efficient TLR4-induced transcriptional upregulation of NLRP3, procaspase-11, and proIL-1$\beta$ (inflammasome priming). At the posttranslational level, FADD functions as a platform for procaspase-8 activation, and they both interact with core components of the Nlrp3 inflammasome to drive stimulus-dependent caspase-1/11 maturation. Inflammasome-activated caspase-1 processes and secretes IL-1$\beta$ and IL-18. Independently of caspase-1, caspase-11 also mediates enteropathogen-induced pyroptosis. *p < 0.05, **p < 0.01, ***p < 0.001.
Together, these results demonstrate that FADD and caspase-8 control pathological disease parameters in at least two in vivo mouse models of human disease that were previously attributed to Nlrp3 inflammasome activation.

Discussion

Caspase-8 was shown to directly mature proIL-1β in macrophages treated with TLR3 and TLR4 agonists in the absence of caspase-1 and Nlrp3 (17) and in response to extracellular fungi and mycobacteria (15). In addition, macrophages exposed to TLR ligands were shown to upregulate expression levels of Fas receptor, which allows significant secretion of mature IL-1β and IL-18 upon subsequent exposure to Fas ligand. Notably, Fas ligand–induced IL-1β and IL-18 secretion from LPS-primed macrophages and dendritic cells relied on caspase-8, whereas RIP3 and the inflammasome components ASC and caspases-1 and -11 were dispensable (16). A similar requirement for caspase-8, independently of ASC and caspase-1, recently was demonstrated for IL-1β secretion from BMDCs that were cocultured with LPS and proapoptotic chemotherapeutic agents, such as doxorubicin and Staurosporine (39). Moreover, when induction of more rapid caspase-1–mediated pyroptotic cell death is prevented, LPS-primed macrophages that are subsequently stimulated with nigericin (a canonical Nlrp3 inflammasome stimulus) or transfected with dsDNA (an activator of the AIM2 inflammasome) undergo caspase-8–mediated apoptosis (19, 40). Notably, caspase-8 physically interacted with the inflammasomes adaptor ASC under these conditions, and ASC, but not caspase-1, was required for caspase-8 maturation in response to LPS+nigericin and cytosolic DNA (19).

Our work clarifies the roles of FADD and caspase-8 in IL-1β production by the regular Nlrp3 inflammasome pathways (Fig. 7E). We showed that FADD and caspase-8 drive potent Nlrp3 inflammasome activation and IL-1β secretion at two regulatory checkpoints. At the transcriptional level, FADD and caspase-8 promoted NF-κB–dependent transcriptional upregulation of proIL-1β. Indeed, defective proIL-1β production also was observed recently to occur in S. typhimurium–infected Rip3−/−Casp8−/− macrophages (37). This likely explains the significantly reduced secretion of mature IL-1β from these cells in the absence of defective caspase-1 maturation by the Nlrc4 inflammasome. In addition to proIL-1β, we noted that LPS-induced transcriptional induction of Nlrp3 expression levels, a necessity for Nlrp3 inflammasome priming, partially depended on FADD and caspase-8. A similar dependency on caspase-8 for transcriptional upregulation of proIL-1β and Nlrp3 was reported recently in LPS-primed BMDCs (39). The transcriptional role of caspase-8 in Nlrp3 inflammasome priming was evident at early time points, and it gained further significance when BMDCs were treated with LPS for extended durations (>8 h) (39). Notably, our observations further revealed that the transcriptional roles of FADD and caspase-8 were not confined to TLR4-induced signaling but extended to NF-κB and MAPK activation by the TLR2 ligand Pam3CSK4 and the NOD2 ligand MDP. Together, these results strongly implicate that FADD/caspase-8 play an accessory role in the activation of caspase-1 and -8 are activated downstream of Nlrp3 and ASC in response to canonical stimuli of the Nlrp3 inflammasome. In agreement, a recent report showed that ASC mediates caspase-8 processing in LPS+nigericin-treated macrophages and physically associates with caspase-8 (19). A similar interaction between caspase-8 and ASC specks recently was reported to occur in macrophages that had been infected with S. typhimurium (37), a pathogen that may activate both the Nlrc4 and Nlrp3 inflammasomes (6, 41). Indeed, we observed that FADD and caspase-8 interacted with core components of the Nlrp3 inflammasome, and caspase-8 was required for caspase-1 activation, as well as for IL-1β and IL-18 secretion. Notably, cFLIP−/−, an interaction partner of caspase-8, recently was demonstrated to interact with the Nlrp3 inflammasome, and hemizygous deletion of cFLIP−/− inhibited canonical Nlrp3 inflammasome activation, as well (42).

Combined with the work presented in this article, it raises the possibility that cFLIP and caspase-8 form a proteolytically active complex that promotes Nlrp3 inflammasome activation, paralleling the cFLIP/caspase-8 complexes suggested to inhibit necroptosis (43) and to promote NF-κB signaling in activated T cells (44, 45). Together with the observation that TNF-α and its receptor were dispensable for Nlrp3 inflammasome activation, our data also suggest that FADD may serve as a platform for caspase-8 autophosphorylation in the inflammasome. In agreement, immunofluorescence micrographs showed caspase-1 and caspase-8 to colocalize in macrophages exposed to canonical and noncanonical activators of the Nlrp3 inflammasome. Notably, enteropathogens differed from canonical Nlrp3 inflammasome stimuli in that they activated caspase-8 independently of Nlrp3 and ASC; further work is needed to dissect the mechanism leading to caspase-8 processing in enteropathogen-infected macrophages. However, our observation that enteropathogen-induced caspase-11 maturation was significantly affected in FADD- and caspase-8−/− deficient cells suggests that these molecules might relay the signal for caspase-11 processing from a recently proposed intracellular LPS receptor of unknown identity (46). Taken together, our results support the hypothesis that FADD and caspase-8 contribute to both NF-κB–dependent priming and posttranslational activation of the Nlrp3 inflammasome. At first glance, this appears to contrast with a recent report (18) suggesting that caspase-8 negatively regulates spontaneous LPS-induced IL-1β secretion in dendritic cells, which was relayed by Rip3. However, the cited report focused on the mechanisms driving “spontaneous” LPS-induced inflammasome activation in caspase-8–deficient dendritic cells in the absence of inflammasome triggers, such as ATP and nigericin (18). Notably, unlike in dendritic cells with a conditional deletion of caspase-8, LPS stimulation alone fails to trigger inflammasome activation in WT and Casp8−/−Rip3−/− macrophages and dendritic cells. Moreover, albeit higher than in WT controls, levels of spontaneously secreted IL-1β in LPS-stimulated Casp8−/− dendritic cells appeared significantly lower than those frequently noted with canonical triggers of the Nlrp3 inflammasome (18). Thus, it is likely that LPS-induced activation of Nlrp3 in the context of caspase-8 deficiency is mechanistically distinct from that leading to robust canonical and noncanonical Nlrp3 inflammasome activation in response to ATP and enteropathogens. Regardless, by identifying FADD and caspase-8 as upstream mediators of canonical and noncanonical Nlrp3 inflammasome priming and activation, our studies provide a framework for understanding how apoptotic and Nlrp3 inflammasome pathways interconnect.

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Disclosures

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References


