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Cutting Edge: Resistance to *Bacillus anthracis* Infection Mediated by a Lethal Toxin Sensitive Allele of *Nalp1b/Nlrp1b*

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Pathogenesis of *Bacillus anthracis* is associated with the production of lethal toxin (LT), which activates the murine *Nalp1b/Nlrp1b* inflammasome and induces caspase-1-dependent pyroptotic death in macrophages and dendritic cells. In this study, we investigated the effect of allelic variation of *Nlrp1b* on the outcome of LT challenge and infection by *B. anthracis* spores. *Nlrp1b* allelic variation did not alter the kinetics or pathology of end-stage disease induced by purified LT, suggesting that, in contrast to previous reports, macrophage lysis does not contribute directly to LT-mediated pathology. However, animals expressing a LT-sensitive allele of *Nlrp1b* showed an early inflammatory response to LT and increased resistance to infection by *B. anthracis*. Data presented here support a model whereby LT-mediated activation of *Nlrp1b* and subsequent lysis of macrophages is not a mechanism used by *B. anthracis* to promote virulence, but rather a protective host-mediated innate immune response. *The Journal of Immunology*, 2010, 184: 17–20.

*Bacillus anthracis* is the pathogenic bacterium responsible for the acute disease anthrax. Virulence of *B. anthracis* is mediated in large part via the production of a protein exotoxin called lethal toxin (LT). Indeed, purified LT induces many symptoms associated with fulminant anthrax including vascular collapse and death (1–3). LT is a bipartite toxin in which the binding subunit, protective Ag (PA), attaches to anthrax toxin receptors and subsequently delivers the catalytic moiety, lethal factor (LF), into the host cell cytosol. Once intracellular, LF functions as a zinc-dependent metalloproteinase, cleaving the N termini of MAPK kinases and thereby disrupting cell signaling through the ERK1/2, JNK, and p38 pathways (3).

As a result, LT cripples the host innate immune system by blocking cytokine production from numerous cell types, inhibiting chemotaxis of neutrophils, and inducing apoptosis in activated macrophages (3). At high concentrations, similar to those found late in infection, LT induces cytokine-independent shock and death in animals that is associated with vascular collapse (1, 2, 4).

Interestingly, LT induces rapid cell lysis in macrophages and dendritic cells derived from a subset of inbred mouse and rat strains (3, 5). This finding led to the model that the cytokine burst resulting from LT-induced macrophage lysis contributes to pathology associated with this toxin (6, 7). Such a model is attractive, as rapid release of proinflammatory cytokines concomitant with macrophage lysis could, in theory, exacerbate the vascular damage associated with anthrax and LT-mediated pathology (3). Furthermore, macrophages play an important role in limiting *B. anthracis* infection (8–10), and their rapid destruction by LT would be predicted to result in increased bacterial fitness. However, this model is at odds with the observations that animals resistant to purified LT are sensitive to challenge by *B. anthracis* spores and vice versa (11). A similar inverse relationship exists in inbred mouse strains whereby many strains whose macrophages lyse in response to LT display increased resistance to infection by *B. anthracis* (12). Therefore, contrary to one model, LT-mediated lysis of macrophages appears to be associated with protection against infection by *B. anthracis*.

A single gene, *Nlrp1b*, controls macrophage and dendritic cell sensitivity to LT (3, 13), and when heterologously expressed with caspase-1 in human fibroblasts, confers susceptibility to LT in these cells (14). *Nlrp1b* is a member of the nucleotide-binding domain–leucine rich repeat family of proteins found in plants, called R proteins, and animals, termed NLR proteins (6, 13). Plant R proteins function in host immunity by recognizing pathogens and/or danger signals and initiating a hypersensitive response that can function locally through induction of cell

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Abbreviations used in this paper: ERP, early response phenotype; IL-1β, β form of pro-IL-1; LF, lethal factor; LT, lethal toxin; LTb, lethal toxin-resistant; LTs, lethal toxin-sensitive; PA, protective Ag; PMN, polymorphonuclear neutrophil.
Materials and Methods

Mouse maintenance and breeding

All mice were cared for in accordance with the University of California Animal Research Committee and the U.S. Army Medical Research Institute of Infectious Diseases Animal Care and Use Committee. C57BL/6j (B6) mice were purchased from the Jackson Laboratory (Bar Harbor, ME). Transgenic mice expressing a 129S1/SvImJ(129S1)-derived lethal toxin-sensitive (LTS) allele of Nlrp1b on a LT-resistant (LT<sup>+</sup>) B6 background (B6<sup>Nlrp1b<sub>129S1</sub></sup>) backcrossed to B6 for seven generations, were obtained from Drs. E. Boyden and W. Dietrich (Harvard Medical School, Boston, MA). Heterozygous Nlrp1b<sup>B6<sub>129S1</sub></sup> mice were intercrossed or crossed with B6, and transgene-positive offspring were identified by PCR genotyping as previously described [13].

Toxin preparation and challenge

PA was expressed in Escherichia coli and purified as previously described [16], followed by Sephacryl S-200 (GE Healthcare, Piscataway, NJ) size exclusion chromatography. LF was obtained from Dr. J. Mogridge (University of Toronto, Toronto, Ontario, Canada). A dose of 5 μg PA and 2.5 μg LF, diluted in pharmaceutical grade saline, per g body weight was injected i.p. Alternatively, PA and LF were purified from B. anthracis strain HA143 [17]. LF produced from strain HA143 displayed 3-fold lower activity [18], and consequently a dose of 15 μg PA and 7.5 μg LF per g body weight was used to achieve a similar mortality rate. Endotoxin was removed from all toxin preparations as described [16]. Walking ataxia was scored as follows: mild: reduced exploratory behavior or rearing on hind limbs, a slow and/or less steady gait, but free ambulation throughout the cage; moderate: preferred sedentary state, but the mouse was able to generate a slow, unsteady (e.g., wobbly) gait usually for ≤7 s before resting; and severe: typically in a stationary state, but on stimulation the mouse could generate a few unstable steps (e.g., severe wobble and/or tremor) before stopping. Body temperatures were measured following LT injection using a rectal thermometer. Baseline temperatures were determined prior to LT administration, and the remaining animals typically presented by 1 to 2 h. Wild-type B6 and littermate control (not shown) animals displayed no significant ERP following LT challenge (Fig. 1B, 1C). Surprisingly, B6<sup>Nlrp1b<sub>129S1</sub></sup> mice recovered from LT challenge more typically following LT administration following LT challenge (Fig. 1B, 1C).

The pathology, timing, and clinical presentations associated with the ERP are consistent with an inflammatory response, the rate of macrophage lysis ex vivo, and the previously reported cytokine response in LT<sup>+</sup> strains of mice [1, 2]. We therefore tested whether expression of a LT<sup>+</sup> allele of Nlrp1b is sufficient to induce a proinflammatory cytokine response to LT. Activation of Nlrp1b results in formation of a caspase-1-containing inflammasome and subsequent proteolytic maturation of the B form of pro-IL-1 (IL-1β) [13, 19]. As expected, IL-1β increased rapidly after LT administration (Fig. 1D). In addition, several proinflammatory cytokines not directly activated by caspase-1 also increased (Fig. 1D) [1, 2]. In contrast to previous findings with LT<sup>+</sup> strains of mice [1, 2], there was a mild increase in TNF-α in B6<sup>Nlrp1b<sub>129S1</sub></sup> mice (Fig. 1D). No changes were observed in either IL-1α or IFN-γ. Endotoxin contamination of PA or LF was not responsible for cytokine induction as no response was detected following injection of a 2× dose of individual toxin components (data not shown). Further, B6 animals showed no ERP or cytokine response to LT (Fig. 1D), indicating that these responses are a result of Nlrp1b detection of LF activity rather than LPS contamination. Therefore, expression of a LT<sup>+</sup> allele of Nlrp1b in LT<sup>+</sup> B6 mice is sufficient to induce a proinflammatory cytokine response to LT in mice.

LT<sup>+</sup> Nlrp1b alleles provide protection against B. anthracis infection

To test the role of Nlrp1b in an infection model, B6<sup>Nlrp1b<sub>129S1</sub></sup> mice and transgene-negative littermate control animals were challenged with the unencapsulated, toxigenic B. anthracis Sterne strain. Within 6 d, eight of nine control animals succumbed to infection, whereas all B6<sup>Nlrp1b<sub>129S1</sub></sup> mice survived for the duration of the experiment (Fig. 2A). To test the role of a LT<sup>+</sup> Nlrp1b allele in response to a fully virulent B. anthracis infection, B6<sup>Nlrp1b<sub>129S1</sub></sup> mice were challenged with B. anthracis Ames strain. Although B6<sup>Nlrp1b<sub>129S1</sub></sup> mice displayed a trend toward protection, the data were not statistically significant (Fig. 2B). The latter finding is not surprising given that virulence associated with the Ames strain is governed primarily by the presence of a poly-D-glutamic acid capsule rather than LT in the mouse model [20].

To determine the cellular mediators contributing to Nlrp1b-mediated resistance to infection, peritoneal exudates were collected and analyzed at various time points following spor...
challenge. Both strains responded with an increase in the number of Ly6G+ PMNs (Fig. 2C). However, the levels of PMNs were higher in B6Nlrp1b Tg mice at early time points following spore challenge compared with nontransgenic littermate control animals. This influx of PMNs was followed by more Ly6G+ Mac1+ monocytes in both strains (Fig. 2D) that were maintained in B6Nlrp1b mice but not control mice.

Discussion

Based on LT and spore-challenge data from different animal species, Lincoln et al. (11) hypothesized that animals resistant to infection by B. anthracis were susceptible to challenge by its toxin and that the inverse was true for infection-susceptible species. Using inbred and recombinant strains of mice, Welkos and colleagues (12, 21, 22) substantiated this proposed inverse correlation between the sensitivity of animals to challenge with purified LT and with B. anthracis spores and explored the genetic basis for this phenomenon. Specifically, mice whose macrophages rapidly lyse in response to LT were more resistant to spore challenge than mice whose macrophages were LT-resistant (12, 13, 23). Further, mice resistant to spore challenge had increased rates of PMN infiltration at early time points and sustained higher monocyte numbers at the site of B. anthracis infections (22). Here we report that allelic variation at Nlrp1b accounts for these previously observed phenomena, thereby providing molecular insight into host defense against anthrax.

B. anthracis triggers activation of TLRs and NOD2 in human and mouse macrophages, resulting in production of TNF-α through a MAPK signaling pathway (24). However, the presence of LT blocks this response by cleaving and inactivating MAPK kinase proteins (24). LT-resistant mice counteract this immunosuppressive effect by triggering a rapid proinflammatory programmed cell death. Interestingly, IL-1β is released upon LT-mediated macrophage lysis (19). IL-1β is a proinflammatory cytokine that recruits PMNs and monocytes, cell types that are predicted to resolve infection (9, 10, 25). Although Nlrp1b inflammasome activation in response to LT is detrimental to the toxin-exposed macrophage, our data demonstrate that Nlrp1b activation is ultimately beneficial for the host by inducing inflammation (e.g., enhanced cytokine production and PMN infiltration) at the site of LT production. Of note, a similar mechanism has been described in plants where R proteins recognize bacterial virulence factors in the host cell cytosol and induce localized cell death to limit infection. Importantly, the finding that the Nlrp1b-mediated inflammatory response is protective against B. anthracis infection is consistent with previous data that mice deficient in caspase-1, IL-1β, or IL-1R display increased sensitivity to anthrax (25, 26). Therefore, we propose that Nlrp1b-mediated cell death provides a selective advantage to the host rather than pathogen.

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