Cutting Edge: Pulmonary *Legionella pneumophila* Is Controlled by Plasmacytoid Dendritic Cells but Not Type I IFN


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Plasmacytoid dendritic cells (pDCs) are well known as the major cell type that secretes type I IFN in response to viral infections. Their role in combating other classes of infectious organisms, including bacteria, and their mechanisms of action are poorly understood. We have found that pDCs play a significant role in the acute response to the intracellular bacterial pathogen Legionella pneumophila. pDCs were rapidly recruited to the lungs of L. pneumophila-infected mice, and depletion of pDCs resulted in increased bacterial load. The ability of pDCs to combat infection did not require type I IFN. This study points to an unappreciated role for pDCs in combating bacterial infections and indicates a novel mechanism of action for this cell type.

Legionella pneumophila is an opportunistic intracellular pathogen in humans and the major cause of Legionnaires’ disease. A combination of innate and adaptive immune responses are critical in controlling L. pneumophila infection in mice, with IFN-γ (1), MyD88 (2, 3), and T cells playing major roles (4). Several in vitro studies have also investigated the role of type I IFN (IFN-I) in restricting L. pneumophila colonization of cells. For example, mouse bone marrow-derived macrophages deficient in the IFN-IR (IFNAR) are more permissive for L. pneumophila replication, and the pretreatment of permissive macrophages with IFN-I inhibits growth of the bacteria (5–7). Also, IFN-β expression is induced upon L. pneumophila infection of mouse macrophages and in a human alveolar basal epithelial cell line (7–10). One aim of this work was to investigate the role of IFN-I in limiting L. pneumophila infection in vivo, as this had not been thoroughly investigated.

A major cell type that produces IFN-I is the plasmacytoid dendritic cell (pDC), a cell type with distinct functional characteristics compared with conventional Ag-presenting DCs (11–13). pDCs may traffic through some tissues in the steady state, but they are rapidly recruited by infection and inflammatory mediators (13). The role of pDCs in different types of infections is still unclear. pDCs produce large quantities of IFN-I in response to viral infections (14, 15); however, some studies have begun to explore the contribution of pDCs to nonviral immune responses. For instance, pDCs are able to recognize bacterial RNA, resulting in the production of IFN-I (16). pDCs also produce IFN-I when exposed to Borrelia burgdorferi in vitro (17). Finally, pDCs can activate CD4+ T cells via Ag presentation and secretion of IL-12 in response to Toxoplasma gondii infection (18). As IFN-I may also be an effector molecule used in the clearance of intracellular bacterial infections, such as L. pneumophila, we studied the role of pDCs in a mouse model of L. pneumophila infection. We demonstrated that pDCs do indeed play a role in combating L. pneumophila, although IFN-I was not required for this effect.

Materials and Methods

Bacteria strains and culture conditions

L. pneumophila strains 130b (ATCC BAA-74) and JR32 and the flagellin mutant ΔflaA JR32 (19) were used for mouse infection studies. GFP-expressing L. pneumophila strain 130b was used for all in vitro infection studies. GFP was expressed from the plasmid pMipA, a derivative of the cloning vector pMAMB207, which was introduced into L. pneumophila 130b by electroporation as described previously (20). All bacterial strains were cultured in ACES-buffered yeast extract broth or on buffered charcoal yeast extract agar.

Mice

A strain mice, C57BL/6 and IFNAR2−/− (21) mice, were obtained from the Department of Microbiology and Immunology or the Bio21 Molecular Science and Biotechnology Institute (University of Melbourne, Parkville, Victoria, Australia) or the Animal Resource Centre (Canning Vale, Western Australia, Australia). All mice were housed under specific pathogen-free conditions, and experiments were conducted with approval from The University of Melbourne Animal Ethics Committee.

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Abbreviations used in this paper: DC, dendritic cell; IFN-I, type I IFN; IFNAR, type I IFN receptor; pDC, plasmacytoid dendritic cell; PDCA, plasmacytoid dendritic cell Ag.
Infection and quantification of *L. pneumophila* in mice

Mice were anesthetized with ketamine and xylazine and restrained on their backs with the larynx illuminated. A 20-gauge catheter was used to intubate the trachea, and 2.5 × 10^6 CFU *L. pneumophila* in 25 μl PBS was slowly injected into the lungs followed by an equal volume of air using a blunt Hamilton syringe. For analysis, lungs and spleens were harvested aseptically and homogenized followed by lysis of cells with 0.05% saponin in PBS. Intracellular *L. pneumophila* were enumerated by serial dilution and plating onto buffered charcoal yeast extract agar.

**In vivo depletion of pDCs**

Mice were depleted of pDC using the mAb 120G8 (22). Mice were injected i.p. with 1 mg/mouse 120G8 mAb or rat IgG (Sigma-Aldrich, St. Louis, MO) the day before infection and were given additional doses of Ab each day after inoculation until mice were killed (Supplemental Fig. 1). Depletion of pDCs in the lung and spleen of 120G8-treated mice was ~95% at 72 h post-infection.

**Flow cytometry**

Single-cell populations from the spleen or lung were generated by enzymatic digestion and labeled with combinations of Abs. Enumeration of cells was calculated based on a known quantity of allophycocyanin-conjugated beads added to each sample. Abs and beads were purchased from BD Pharmingen (San Diego, CA) or eBioscience (San Diego, CA). Cells were analyzed on a CyAn ADP Analyzer (Beckman Coulter, Fullerton, CA) using Summit software.

**Enrichment of DCs and macrophages for in vitro infection**

DCs were enriched by Nylon medium (Nycosmed, Oslo, Norway) centrifugation from collagenase-DNase digests of spleen as previously described (23). Macrophages were harvested from mouse peritoneal washes. Cells were incubated with the GFP-expressing *L. pneumophila* at a multiplicity of infection of 50 at 37°C for 2 h using RPMI 1640 media supplemented with 10% FCS and glutamine in microcentrifuge tubes. DCs were seeded into 96-well tissue culture plates at a density of 1–1.5 × 10^5 cells/well. Macrophages were isolated by adherence purification on coverslips before confocal microscopy. Cells were cultured in RPMI 1640 media for 24 h at 37°C and 5% CO2 before analysis.

**Confocal microscopy**

*L. pneumophila*-infected DCs were labeled with anti-pDC Ag (PDCA)-1 and allowed to adhere onto coverslips coated with anti-MHC class II Ab (eBioscience). *L. pneumophila*-infected macrophages were labeled with anti-CD45. Cells were fixed in 4% paraformaldehyde, and images were acquired using a Leica LCS SP2 confocal laser-scanning microscope (Leica Microsystems, Deerfield, IL).

**Statistical analysis**

Two-tailed Mann-Whitney *U* tests were performed using Prism software (GraphPad, San Diego, CA). Comparisons giving *p* values ≤0.05 were considered significant.

**Results**

**pDCs are recruited rapidly into the lungs of *L. pneumophila*-infected mice**

To determine if pDCs were recruited during *L. pneumophila* infection, lung infiltrates were analyzed at 24 h and 72 h after infection. Significant increases in the number of CD45^-CD11c^hiMHCII^int^PDCA-1^-CD11b^- F4/80^- pDCs were observed at 24 and 72 h after infection compared with mock-infected mice (representative flow cytometric plots are shown in Supplemental Fig. 2; enumeration is shown in Fig. 1). The mean number of pDCs increased by ~4-fold in the lungs of infected mice at 72 h compared with 24 h, suggesting an active recruitment of pDCs during the course of infection. Recruitment of pDCs into the lung during influenza virus and respiratory syncytial virus infection has been reported (24–26), but this is the first report of pDCs infiltrating the lung during a bacterial infection.

**pDCs are infected by *L. pneumophila***

*L. pneumophila* can infect bone marrow-derived DCs, a heterogeneous population that may include pDCs (19, 27–29). To discover if *L. pneumophila* can infect pDCs, splenocytes from *L. pneumophila*-infected strain mice were enriched for DCs by density gradient centrifugation and cultured with GFP-expressing *L. pneumophila* strain 130b. The DC-enriched splenocytes were then labeled with anti–PDCA-1 and anti-CD11c mAb for flow cytometry as described in Supplemental Fig. 2. The total number of pDCs detected in the lungs of *L. pneumophila*-infected and control mice at 24 and 72 h after infection are shown. Each circle represents a single mouse. Mean ± SEM is shown. Data are pooled from four independent experiments. **p < 0.001.

**pDCs restrict *L. pneumophila* infection in vivo**

pDCs are important agents in combating viral infections via the production of IPN-I (14, 15). To determine if pDCs play a role in the immune response against *L. pneumophila*, a strain mice were depleted of pDCs with mAb 120G8 before infection with *L. pneumophila*. The details of Ab treatments used for

**FIGURE 1.** pDCs are recruited into the lung after *L. pneumophila* infection. A strain mice were infected with 2.5 × 10^6 CFU *L. pneumophila* 130b per mouse. Mock-infected mice received PBS. At 24 and 72 h after infection, lungs were harvested and analyzed for the presence of pDCs by flow cytometry as described in Supplemental Fig. 2. Total number of pDCs detected in the lungs of *L. pneumophila* infected and control mice at 24 and 72 h after infection are shown. Each circle represents a single mouse. Mean ± SEM is shown. Data are pooled from four independent experiments. **p < 0.001.
pDCs had more severe systemic infection at 48 h after infection as evidenced by an ~8-fold increase in splenic bacteria load compared with control mice (depleted: n = 8, 95.0 ± 41.4 CFU versus control: n = 10, 12.0 ± 6.8 CFU; p = 0.03).

**IFN-I is not essential for immunity against L. pneumophila**

To determine if IFN-I plays a role in the immune response against *L. pneumophila*, we used mice deficient for the IFN-IR (IFNAR2<sup>−/−</sup>) on the C57BL/6 background. To obtain robust infection of C57BL/6 mice, we used a flagellin-deficient (ΔflaA) mutant of *L. pneumophila*. C57BL/6 mice have a more active flagella-sensing Nalp5/Birc1e compared with A strain mice and thus are able to clear wild-type bacteria more effectively (30, 31). The flaA mutant was derived from the *L. pneumophila* JR32 strain, so we verified that infection by *L. pneumophila* JR32 is restricted by pDCs in a similar manner to the 130b strain in A mice (Supplemental Fig. 4). Subsequently, IFNAR2<sup>−/−</sup> mice were infected with ΔflaA *L. pneumophila*. No significant differences in the number of *L. pneumophila* CFU were detected in the lungs of IFNAR2<sup>−/−</sup> mice compared with control C57BL/6 mice at 48 h after infection (Fig. 4A).

To prove that the control of *L. pneumophila* infection by pDCs did not require IFN-I, IFNAR2<sup>−/−</sup> mice were depleted of pDCs using the 120G8 mAb treatment (Supplemental Fig. 1) before infection with ΔflaA *L. pneumophila*. Similar to A strain mice at 48 h after infection, the lungs of pDC-depleted IFNAR2<sup>−/−</sup> mice contained significantly higher numbers of *L. pneumophila* compared with nondepleted controls (Fig. 4B).

**Discussion**

Recently, several reports have indicated that *L. pneumophila* induces IFN-I in infected cells and that IFN-I may help control infection. In this study, we have shown that in a mouse model,
IFN-I does not appear to be required to limit *L. pneumophila* replication during the acute phase of infection (Fig. 4). This work is consistent with a recent report showing that mice deficient in molecules essential to IFN-I production and signaling were colonized to levels similar to that of control mice by *L. pneumophila* (32). Sporri et al. (33) also found IFNAR deficiency did not influence *L. pneumophila* colonization of the spleen in the less physiological i.v. infection model. It seems likely that in normal mice, other cytokines, such as TNF-α and IFN-γ, are sufficient to mediate clearance (1). Whether this is true in humans or immunocompromised individuals remains to be determined.

We established that pDCs were recruited to the lung early in infection by *L. pneumophila* (Fig. 1) and that pDCs played a significant role in controlling *L. pneumophila* replication and persistence in mice (Figs. 3, 4). The main reported modes of action of pDCs in combating infection are the secretion of IFN-I and/or the presentation of peptides derived from pathogens to T cells. In this study, we ruled out a requirement for the former mechanism, as IFNAR2−/− mice depleted of pDCs had increased bacterial load relative to nondepleted IFNAR2−/− mice (Fig. 4B). A T cell-dependent mechanism also seems unlikely given the short time frame of our experiments. The effects of pDCs were apparent within 48 h of infection, which is too early for an adaptive T cell-mediated response. One alternative mechanism is that pDCs produce cytokines other than IFN-I that can be used to combat bacteria. Little attention has been paid to pDC cytokine production other than IFN-I, but pDCs do produce IL-12 (18, 32). Our work has demonstrated that pDCs can combat an infection by *L. pneumophila* (Fig. 1) and that pDCs played a significant role in controlling *L. pneumophila* replication and infection by aerosolized *Legionella pneumophila*. *J. Infect. Dis.* 193: 1633–1670.

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**Disclosures**

The authors have no financial conflicts of interest.

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Supplementary Figures

Figure 1: Schedule of treatments for mice administered with 120G8 mAb. Mice were injected i.p. with 1 mg/mouse of the pDC depleting 120G8 mAb 24 h before infection with $2.5 \times 10^6$ CFU of *L. pneumophila*. Control mice received Rat IgG. (i) At 24 h after infection, lungs were harvested and the bacteria load determined. Additional doses of antibody were administered as indicated for analysis at 48 h (ii) and 72 h (iii) after infection.
Figure 2: Plasmacytoid DC are recruited into the lung after *L. pneumophila* infection. A mice were infected with $2.5 \times 10^6$ CFU of *L. pneumophila* strain 130b per mouse. Control mice received PBS. At 24 h and 72 h after infection, lungs were harvested and analysed for the presence of pDC by flow cytometry. Representative density plots show the presence of CD11c<sup>int</sup>PDCA-1<sup>+</sup> pDC in infected mice. Plots are gated on CD45<sup>+</sup>CD11b<sup>−</sup>F4/80<sup>−</sup> cells followed by a lymphocyte gate.
Figure 3: Gating strategy used to define \textit{L. pneumophila} infected cells. Splenocytes from A mice were enriched for DC by density gradient centrifugation and cultured with GFP-expressing \textit{L. pneumophila} strain 130b for 2 h. Cells were then washed and cultured for 24 h before analysis by flow cytometry. Figure displays representative plots of the gating strategy used to define pDC (PDCA-1$^+$CD11c$^{int}$), cDC (PDCA-1$^+$CD11c$^{hi}$) and non-DC (PDCA-1$^+$CD11c$^-$) and the proportion of \textit{L. pneumophila} infected cells as measured by GFP expression within those cell populations.
**Figure 4: Plasmacytoid DC restrict* L. pneumophila strain JR32* infection.** A mice were injected i.p. with 1 mg/mouse of 120G8 mAb according to supplementary Fig 1ii and infected with 2.5 x 10^6 CFU of *L. pneumophila* strain JR32. Control mice received Rat IgG. 48 h after infection, lungs were harvested and the bacteria load determined. Each circle represents a single mouse. The total number of *L. pneumophila* CFU detected in the lungs of infected mice is shown. Mean ± SEM is shown. *** denotes p value < 0.0005.