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Ectopic lymphoid tissue formation in the lungs of mice infected with *Chlamydia pneumoniae* is associated with epithelial macrophage inflammatory protein-2/CXCL2 expression

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Summary
Infection with *Chlamydia pneumoniae* (Cp) accounts for around 10% of community acquired bacterial pneumonia and has been associated with other chronic inflammatory conditions. We describe a C57/Bl6 murine model of Cp lung infection characterized by a dose-dependent, resolving neutrophilia followed by lymphocytic infiltration of the lungs. By 21 days post-infection, mice exhibit a T helper type 1 (Th1) polarized serum antibody response with local mucosal antibody secretion and organization of ectopic lymphoid tissue which persisted in the absence of detectable Cp DNA. Macrophage inflammatory protein (MIP)-2/CXCL2, which recruits neutrophils and lymphocytes and is associated with ectopic lymphoid tissue formation, was secreted in the lungs post-infection.

In vitro, lung epithelial cells up-regulated MIP-2/CXCL2 in response to both rough lipopolysaccharide (reLPS) and Cp infection. We conclude that Cp infection can have long-term inflammatory effects on tissue that persist after clearance of active infection.

Keywords: *Chlamydia pneumoniae*, CXCL2/MIP-2, epithelium, lung, lymphocytes

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Introduction
*Chlamydia pneumoniae* (Cp), an obligate intracellular bacterium, is a ubiquitous human pathogen [1]. Cp infection accounts for around 10% of community acquired bacterial pneumonia and has been associated with chronic lung diseases including chronic bronchitis [2], asthma [1] and chronic obstructive pulmonary disease (COPD) [3] and other chronic pathologies, including multiple sclerosis [4], atherosclerosis [5] and Alzheimer’s disease [6]. Despite these associations, antibiotic therapy does not have a major clinical benefit in these disorders [7–9], and where an effect has been observed, such as with macrolides [10,11] it is unclear if this is due to anti-microbial or anti-inflammatory effects [12]. It is possible that pulmonary Cp infection initiates an inflammatory environment which persists after bacterial clearance and contributes to infection-associated pathology.

Several murine models of Cp ‘vaccination’, infection and reinfection have been published [13–15] and have established that Cp infects lung epithelial cells and induces lung inflammation, ectopic lymphoid tissue formation and airway hyper-reactivity. However, there is little information on how resolution of infection relates to inflammation-induced disruption of lung architecture which may contribute to pathology.

We investigated a link between cytokine production by Cp-infected lung epithelial cells and inflammation. The chemokine macrophage inflammatory protein (MIP)-2/CXCL2 recruits both neutrophils and lymphocytes [16–18] and is associated with ectopic lymphoid tissue formation [19]. It has been reported that epithelial cell secretion of MIP-2/CXCL2 recruits both lymphocytes and neutrophils to the gut [18]. Here we report that murine Cp lung infection induced systemic T helper type 1 (Th1)-driven immunity, local mucosal antibody secretion and initiated organization of ectopic lymphoid tissue which persisted in the absence of detectable Cp DNA. We demonstrated that MIP-2/CXCL2 was secreted in the lungs post-infection (PI). Furthermore, *in vitro* studies utilizing lung epithelial cell lines demonstrated up-regulation of MIP-2/CXCL2 in response to both Cp infection and to a rough form of LPS (reLPS) analogous to that expressed by Cp.

Materials and methods
Reagents and plastics
Unless stated, plastics were from Costar (Fisher Scientific, Loughborough, UK), culture reagents from Invitrogen (Paisley, UK) and other reagents from Sigma (Poole, UK).
**Bacteria**

HEp2 cell (ECACC, Salisbury, UK) monolayers were washed and incubated with diethylaminoethyl (DEAE)-dextran 30 μg/ml in Hanks’ balanced salt solution (HBSS) (20 min, room temperature). DEAE-dextran/HBSS was removed and Cp AR39 strain (ATCC 53592) in infection medium [5% fetal calf serum (FCS)/Iscove’s modified Dulbecco’s medium (IMDM)/1 μg/ml cycloheximide] added for 3 h and then replaced with fresh infection medium alone. Infected monolayers were disrupted manually with glass beads. The suspension was centrifuged at 200 g/10 min/4°C, the supernatant centrifuged further at 22 000 g/40 min/4°C, the resulting pellet resuspended in sucrose–phosphate–glutamate buffer [20] medium and stored at −80°C. Uninfected HEp2 lysate was used as a control. Stocks were titrated in Hep2 cells as described for *C. abortus* [21]. Titres of stocks were 7 × 10^10–10^11 inclusion-forming units (IFU)/ml. Cp were inactivated by exposure to 2 ml/mg/cm^2 under an ultraviolet (UV)-cross-linker.

**In vivo infection**

Six to 8-week-old C57Bl/6 mice, bred and maintained under standard specific pathogen-free conditions, were used with local ethical and UK Home Office approval. Fifty μl phosphate-buffered saline (PBS), containing live or UV-inactivated Cp, or control lysate, was instilled into the trachea under anaesthetic. Mice were killed at various times post-infection (dpi=0, 2, 3, 4, 7, 10, 16, 20, 37) in Hanks’ balanced salt solution (HBSS) (20 min, room temperature) and antigen retrieved. Antibodies to Cp rough LPS (reLPS) are cross-reactive with *Salmonella minnesota* rough LPS antibodies [25], which was used to measure antibody responses to infection. Ninety-six-well ELISA plates were coated with 100 ng/well reLPS in pH9-6 carbonate/bicarbonate buffer (overnight, 4°C), washed, blocked (1 h, room temperature) with 1% bovine serum albumin (BSA), washed, serum or BALF dilutions added (overnight, 4°C), washed, biotinylated anti-mouse immunoglobulin IgG1 (Serotec, Oxford, UK), biotinylated anti-mouse IgG2a or biotinylated anti-mouse IgA (both BD Biosciences) added (1 h, room temperature), washed, streptavidin–horseradish peroxidase (HRP) (Dako) added, washed, and staining visualized with diaminobenzidine substrate solution (Dako).

**Assessment of lung inflammation**

As described [22], inflammation was scored by an observer blinded to experimental details (S. E. M. H.) in perivascular and peribronchiolar tissue (1 = 0, 2 = < 20, 3 = > 20 < 100 and 4 = > 100 infiltrating cells) on haematoxylin and eosin (H&E)-stained 3-μm sections at x200 magnification by averaging the score of 10 consecutive fields where the lungs were inflated correctly and the field contained a complete transection of at least one bronchiole (< 300 μm diameter). Neutrophilia was determined as percentage of infiltrating cells.
tetramethylbenzidine; R&D Systems) added (30 min, 37°C, in the dark). The reaction was stopped by addition of 2 N H₂SO₄ and plates read at 450 nm (650 nm reference) on a Biotek Synergy HT plate reader (Fisher Scientific).

**In vitro** LPS treatment and infection

Cells were cultured in a humidified incubator at 37°C in 5% CO₂. Mycoplasma-free, C57Bl/6 derived pulmonary epithelial cell lines, mtCC1-2 [26] and CMT64/61 (ECACC) were maintained in antibiotic-free IMDM containing 10% FCS and 1% L-glutamine (complete IMDM); 250 μl complete IMDM, containing 2.5 × 10⁵ cells, was plated into 48-well plates, cultured for 24 h, medium removed, fresh medium containing reLPS (10 μg/ml), or Cp (at MOI 10), or control lysate, added to triplicate wells and cultured for various times.

MIP-2/CXCL2-2 protein and m-RNA detection

MIP-2/CXCL2 protein was detected using R&D Systems murine Duoset ELISA. RNA (extracted using RNeasy microkit; Qiagen) was run in triplicate multiplex reactions (25 μl containing TaqMan reagents and 40 ng cDNA) in an Applied Biosystems 7500 real-time PCR machine. Gene expression normalized to 18SRNA was linearized to give fold change relative to a value of 1 assigned to expression in cultures grown in medium alone.

**Statistics**

Results were analysed by unpaired *t*-test with Welch’s correction using Graphpad Prism™ software.

**Results**

**In vivo infection**

Dose-dependent BALF neutrophilia was resolving by day 6 PI, whereas the % of lymphocytes, although small, increased from day 3 to day 6 (Fig. 1a–c). Subsequently a dose of 2.5 × 10⁶ IU was used; this induced severe neutrophilia which was not seen with UV-inactivated Cp (Fig. 1d). BALF neutrophilia 3 days PI correlated with chlamydial 23S DNA in lungs from the same animals (Fig. 1e). Bacterial DNA declined after infection and by 21 days PI was undetectable in five of 10 animals (Fig. 1f).

Cp lung infection induces systemic IgG2a and local IgA antibody

Twenty-one days PI, high-titre anti-reLPS IgG2a, but not IgG1, antibodies were detected in serum from infected mice (Fig. 2a,b). There were no detectable anti-reLPS serum IgA antibodies, but high levels were seen in BALF from infected mice (Fig. 2c).

Kinetics of the inflammatory response to Cp infection in lung tissue

Sham-infected mice showed no inflammation at any time, so sham data have been pooled. Figure 3a–g shows inflammation in BALF where total cells and neutrophilia peaked 3 days PI and returned to normal by 21 days PI whereas lymphocytes remained raised 21 days PI. The macrophage number did not differ from the sham-infected controls. Levels of the macrophage chemokine MCP-1 did not differ between BALF from infected or uninfected animals (not shown).
Inflammation in lung interstitium (Fig. 3h–j) also showed neutrophilia that peaked on day 3 and resolved by day 21 PI. In contrast, perivascular and peribronchiolar inflammation did not resolve by day 21 PI.

Cp infection induces formation of ectopic lymphoid tissue

Lungs from mice 21 days PI showed multiple, patchy lymphocytic aggregates. The percentage of blood vessels (mean number/section, 78 ± 7) and bronchioles (mean number/section, 34 ± 4) associated with >10 T lymphocytes (on anti-CD3 stained sections) and with >10 B lymphocytes (on anti-B220 stained sections) were determined. The percentage of blood vessels or bronchioles associated with either cell type was <1 for sham-infected mice, whereas 30–40% of blood vessels and 10–20% of bronchioles in infected mice had associated lymphoid aggregates (Fig. 4a,b). Many aggregates were large, morphologically resembled germinal centres (Fig. 4c,d) and contained clusters of B lymphocytes (Fig. 4e) and scattered T lymphocytes (Fig. 4f). Large numbers of cells were positive for IgA (Fig. 4g) and staining for CD138 (a marker of antibody secreting plasma cells and of lung bronchiolar epithelial cells [27,28]) revealed positive plasma cells indicating ectopic lymphoid tissue formation (Fig. 4h).

Lymphoid aggregates, anti-reLPS antibodies and lymphocytes in BAL do not correlate with detection of 23S chlamydial DNA

Twenty-one days PI, approximately half the mice had no detectable chlamydial 23S DNA in the lungs. There were no differences between IgA in BALF, IgG2a in serum (Fig. 5a), total BALF lymphocytes (Fig. 5b) or distribution of lymphoid aggregates (Fig. 5c,d) in mice that were positive or negative for detection of chlamydial 23S DNA in the lungs 21 days PI.
Infected lungs and airway epithelial cells secrete MIP-2/CXCL2 in response to reLPS and Cp infection

The principal site of infection detected by anti-LPS staining was bronchial epithelial cells (BECs) (Fig. 6a). At 3 days PI, both BECs and alveolar cells contained MIP-2/CXCL2 (Fig. 6b) but at 21 days PI only BECs were positive (Fig. 6c). MIP-2/CXCL2 protein was detected in BALF 1, 3 and 6 days PI (Fig. 6d).

In vitro, reLPS induced upregulation of MIP-2/CXCL2 mRNA (Fig. 6e) and protein secretion (Fig. 6f) in two different mouse lung epithelial cell lines. Protein secretion also increased in response to Cp infection (Fig. 6g).

Discussion

Pulmonary Cp infection induced a dose-dependent, resolving neutrophilia followed by a lymphocytic lung infiltration.

Fig. 5. 23S DNA-positive (black circles) and -negative (open circles) lungs. (a) Bronchoalveolar fluid (BALF) immunoglobulin (Ig)A (1:30 dilution) and serum IgG2a (1:300 dilution) anti-rough lipopolysaccharide (reLPS) antibody enzyme-linked immunosorbent assay, (b) Total number of lymphocytes in BALF (c) Percentage of bronchioles associated with lymphoid aggregates. (d) Percentage of lung blood vessels associated with lymphoid aggregates. Each circle represents an individual mouse.
Macrophages in BALF did not change, indicating that macrophage recruitment may not play a significant role in Cp clearance. Alternatively, Cp may have developed defence mechanisms to ensure that macrophages are not recruited by the inflammatory process that follows lung epithelial cell infection. The lack of local MCP-1 up-regulation by Cp infection may support the latter hypothesis. Failure to recruit macrophages during neutrophilia could result in delayed clearance of apoptotic neutrophils, impacting negatively upon the resolution of inflammation. Cp infection induced serum IgG2a and lung IgA antibodies to reLPS, indicating that the systemic antibody response was Th1-driven and that there was a local mucosal response.

Ectopic lymphoid tissue is a feature of chronic inflammation [29]. In this model Cp lung infection favoured development of ectopic lymphoid tissue which secreted IgA locally in the absence of detectable bacterial 23S DNA. Although we cannot exclude a level of infection below the sensitivity of the PCR-based detection method used, it may be that the lymphoid tissue is maintained by an inflammatory process that once initiated does not require active infection. Ectopic lymphoid tissue formation has been reported by others after reinfection of mice with Cp [13,14]. Here we explored a role for infected lung epithelium in this process. Various signals are necessary for ectopic lymphoid tissue formation in inflammatory settings [30], but the initiating mechanisms are not understood completely. MIP-2/CXCL2 is important for recruitment of neutrophils and lymphocytes by gut epithelial cells [18]; in lymphocyte trafficking during autoimmune responses [16]; and for recruitment of lymphocytes to peripheral organs in graft-versus-host disease [17]; and has been implicated in the neo-angiogenesis associated with ectopic lymphoid tissue formation [19]. The finding that Cp infection induces lung epithelial cell expression of MIP-2/CXCL2 and secretion both in vivo and in vitro suggests a mechanism by which both neutrophilia and lymphocytosis may develop and formation of ectopic lymphoid tissue may be initiated by Cp infection of lung epithelial cells in vivo. Ectopic lymphoid tissue which disrupts the lung architecture may itself cause signs of disease. Thus MIP-2/CXCL2 induced by Cp infection may initiate lymphocytic lung infiltration that can have long-term effects on tissue after clearance of active infection.

Disclosure

None of the authors has any conflict of interest to disclose.

References