Protective Immunity against *Chlamydia trachomatis* Can Engage Both CD4+ and CD8+ T Cells and Bridge the Respiratory and Genital Mucosae

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Understanding the cellular populations and mechanisms responsible for overcoming immune compartmentalization is valuable for designing vaccination strategies targeting distal mucosae. In this study, we show that the human pathogen Chlamydia trachomatis infects the mucrine respiratory and genital mucosae and that T cells, but not Abs, elicited through intranasal immunization can protect against a subsequent transcrvical challenge. Unlike the genital infection where CD8+ T cells are primed, yet fail to confer protection, we found that intranasal priming engages both CD4+ and CD8+ T cells, allowing for protection against genital infection with C. trachomatis. The protection is largely dependent on IFN-γ secretion by T cells. Moreover, different chemokine receptors are critical for C. trachomatis–specific CD4+ T cells to home to the lung, rather than the CXCR3- and CCR5-dependent migration observed during genital infection. Overall, this study demonstrates that the cross-mucosa protective immunity against genital C. trachomatis infection following intranasal immunization is not dependent on Ab response but is mediated by not only CD4+ T cells but also by CD8+ T cells. This study provides insights for the development of vaccines against mucosal pathogens that threaten reproductive health worldwide. The Journal of Immunology, 2015, 194: 2319–2329.

Mucosal surfaces serve as both entry and transmission routes for most pathogens. Therefore, an important aspect in designing effective vaccines against these pathogens is the stimulation of immunity at the relevant mucosal sites. Although there are studies suggesting that systemic immunization can provide mucosal protection (1), others have suggested that mucosal immunization is required for effective T cell–dependent mucosal immunity (2).

There are important distinctions between different mucosal tissues. For example, the lower respiratory and upper genital tracts are relatively sterile and intolerant of flora compared with the gastrointestinal tract. Another example is the distinctive lymphoepithelial structure of the intestinal Peyer’s patches, in contrast to the genital mucosa that lacks organized lymphoid elements. T cell migration among mucosal surfaces is also tightly regulated by the interaction of adhesion molecules and chemokine receptors that are differentially expressed on T cells and their target tissues (3, 4). For instance, skin-homing T cells express ligands for E- and P-selectins, as well as the chemokine receptors CCR4 and CCR10 by the interaction of adhesion molecules and chemokine receptors that are differentially expressed on T cells and their target tissues (3, 4). For instance, skin-homing T cells express ligands for E- and P-selectins, as well as the chemokine receptors CCR4 and CCR10 (5–7), whereas gut-homing effector and memory cells express the αvβ3 integrin and CCR9 chemokine receptor (8, 9).

Despite these differences, the presence of shared immune elements between mucosal sites is also well recognized. For instance, other than well-described skin-homing properties, the E- and P-selectins are also involved in the migration of activated T cells to the peritoneal cavity during inflammation (6). Furthermore, the ability to use remote-site immunization to generate protective immunity at a distinct tissue also suggests that there are aspects of the immune system shared by various mucosal surfaces (10–12).

Intranasal immunization with Neisseria gonorrheae, Chlamydia trachomatis, or HIV Ags has been shown to confer some protection in the genital tract and the protection is correlated with mucosal Ab responses and sometimes heightened cell-mediated responses (10, 12, 13). However, it is not clear which of these elevated responses is responsible or sufficient for cross-mucosal protection.

Given its ability to infect several mucosal sites, C. trachomatis provides a unique opportunity to explore how tissue-specific immunity might be overcome. C. trachomatis is responsible for significant morbidity worldwide. Infection of the ocular epithelium causes blinding trachoma, and infection of the genital mucosa can result in ectopic pregnancy and infertility (14–18). Moreover, when infection of pregnant women is not detected, perinatal transmission of C. trachomatis to the lungs of the newborn can ultimately result in pneumonia (19).

Using murine infection models, researchers have shown that although Abs can provide limited protection against Chlamydia species (20, 21), the host response to C. trachomatis infection is primarily dependent on IFN-γ (22–26). Both CD4+ and CD8+ T cells are stimulated during infection and secrete IFN-γ. However, elimination of CD8+ T cell response does not appear to compromise protection against Chlamydia genital infection (20, 27, 28). In contrast, CD4+ T cells are both necessary and sufficient to confer protection against subsequent infection (22, 29). The signals that govern CD4+ T cell trafficking to the genital mucosa have not been completely elucidated, but it is known that efficient...
migration of *C. trachomatis*-specific CD4$^+$ T cells to the genital mucosa requires the expression of both CXCR3 and CCR5 (30). In the present study, we explore the signals mediating homing of T cells to another mucosal site, the respiratory tract, and show that cross-mucosal protection can be induced in the genital tract through IFN-γ secreted by not only CD4$^+$ T cells but also by CD8$^+$ T cells.

**Materials and Methods**

**Mice**

C57BL/6J, B6.PL-Tnfrsf1a<sup>−/−</sup>CyJ (CD90.1), B6.SJL-Pepck<sup>−/−</sup>BoyJ (CD45<sup>−/−</sup>, B6.129S2-Ighm<sup>−/+</sup>Igλ<sup>−/−</sup>/J (μ<sup>−/−</sup>), B6.129S7-Ighm<sup>−/+</sup>Igλ<sup>−/−</sup>/J (λ<sup>−/−</sup>)), B6.129S7-Igκ<sup>−/+</sup>Iγ<sup>−/−</sup>/J (R<sup>−/−</sup>)), B6.129P2-Cxcr3<sup>−/+</sup>/J (CXCR3<sup>−/−</sup>), and B6.129P2-Cxcr3<sup>−/−</sup>/J (CXCR3<sup>−/−</sup>) mice were purchased from The Jackson Laboratory (Bar Harbor, ME). NR1 transgenic mice expressing a TCR transgene specific for the *C. trachomatis* major outer membrane protein were obtained from Dr. S. Reiner (BOSTON UNIVERSITY). All experiments in this study were approved by Harvard’s Institutional Animal Care and Use Committee.

**Growth, isolation, and detection of bacteria**

*C. trachomatis* serovar L2 (434/Bu) was propagated within McCoy cell monolayers as previously described (30, 31). Aliquots of purified elementary bodies were stored at −80°C in medium containing 250 mM sucrose phosphate glutamate buffer (SPG).

**Infection of mice and preparation of tissue**

For intranasal inoculation, mice were fed with 5% isoflurane (Vedco, St. Joseph, MO) in oxygen and inoculated with 40 μl SPG containing 10<sup>6</sup> inclusion-forming units (IFU) *C. trachomatis*, unless otherwise stated, onto the external nares. For leukocyte quantitative lung tissues were perfused with 3 ml ice-cold PBS before harvest. Lungs were meshed in between microscope slides, enzymatically dissociated in HBSS/Cal/Mg containing 1 mg/ml type XI collagenase and 50 Kunitz/ml DNase (Sigma-Aldrich) for 45 min at 37°C, and washed in PBS containing 5 mM EDTA.

To infect the genital tract, mice were treated s.c. with 2.5 mg medroxyprogesterone acetate (Pfizer, New York, NY) and infected trans-cervically 1 wk later as previously described (29). Briefly, 10 μl SPG containing 5 × 10<sup>6</sup> IFU *C. trachomatis* was deposited using an NSET pipette tip (Paratechs, Lexington, KY). Uteri were minced with scalpels and enzymatically dissociated in HBSS/Cal/Mg containing 1 mg/ml type XI collagenase and 50 Kunitz U/ml DNase (Sigma-Aldrich) for 45 min at 37°C, and washed in PBS containing 5 mM EDTA.

To determine *C. trachomatis* levels in systemic organs, peripheral blood was collected in 10% sodium citrate, lysed with 100 U mutamylsin, and processed with a QIAamp DNA mini kit (Qiagen, Valencia, CA). Spleen, stomach, liver, uterus, and lymph nodes were homogenized by mechanical disruption before DNA extraction with the QIAamp DNA mini kit (Qiagen).

**Flow cytometry**

After isolation, cells were immediately stained for surface and activation markers. For intracellular cytokine staining, cells were stimulated for 4–5 h with 50 ng/ml PMA (Enzo Life Sciences, Farmingdale, NY) and 500 ng/ml ionomycin (EMD Millipore, Darmstadt, Germany) in the presence of brefeldin A (BioLegend, San Diego, CA). Abs were purchased from BioLegend except for CD16/CD32 (Bio X Cell, West Lebanon, NH), anti-CD4 Qdot 605 (Invitrogen), and anti–IFN-γ allophycocyanin-Cy7 (BD Biosciences, San Jose, CA). Cells were preincubated with CD16/CD32 (2.4G2) before staining with fluorochrome-conjugated Abs against CD4 (RM4-5), CD8 (53-67), CD90.1 (OX-7), CD90.2 (53-2.1), CD11b (M1/70), Gr1 (RB6-8C5), CD11c (N418), F4/80 (BMS), NK1.1 (PK136), MHC class I-A<sup>b</sup> (AF6-120.1), CD127 (A7R34), CD62L (Mel-14), or D<sup>d</sup>/ASFPVNPYL (CpAα1.71) MHC class I tetramer. A Live/Dead fixable aqua dead cell stain kit (Invitrogen) was used to exclude dead cells. Intracellular staining, cells were permeabllized with a Cytofix/Cytoperm Plus kit according to the manufacturer’s instructions (BD Biosciences) and stained with anti–IFN-γ (XMG 1.2). The absolute cell number was determined using AccuCheck counting beads (Invitrogen). Data were collected on an LSR II (BD Bioscience) and analyzed using FlowJo (Tree Star, Ashland, OR).

**T cell or IFN-γ depletion**

All Abs were from Bio X Cell. For T cell depletion, immune mice were injected i.p. with 200 μg anti-CD4 (GK1.5), anti-CD8 (2.43), or isotype control (LTF-2) in 200 μl PBS, starting 5 d before secondary challenge and every other day after the secondary challenge. One, 3, and 5 d prior to secondary challenge, each mouse also received 10 μg depleting or control Abs transcervically in 10 μl PBS. T cell depletion was confirmed in the secondary lymphoid organs (SLOs) and uterus by flow cytometry.

For IFN-γ depletion, intranasally immunized mice were injected i.p. with 250 μg anti–IFN-γ (XMG1.2) or isotype control (HRPN) in 200 μl PBS every other day starting 3 d before secondary challenge. XMG1.2 or HRPN Abs (12.5 μg in 10 μl PBS) were also delivered transcervically on days 1 and 3 before secondary challenge. IFN-γ depletion was confirmed in the sera by ELISA as previously described (33).

**T cell or serum transfer**

For transgenic T cell transfer, *C. trachomatis*-specific CD4$^+$ T cells were isolated from the SLOs of NR1 mice. Recipient mice were injected i.v. with 10<sup>5</sup> cells 1 d before infection. For polyclonal T cell transfer, SLOs were isolated from naive or immune mice and homogenized into single-cell suspensions. CD4$^+$ or CD8$^+$ T cells were isolated using mouse CD4 or CD8 negative isolation kits (Invitrogen). Isolated cells were labeled with 10 μM CFSE (Invitrogen) as previously described (22). Pertussis toxin (Ptx) treatment was performed as previously described (34). Unless otherwise stated, 5 × 10<sup>6</sup> CD4$^+$ or 3 × 10<sup>6</sup> CD8$^+$ T cells were injected i.v. into naive mice 4 h before transfervcinal infection. For serum transfer, sera were extracted from peripheral blood of naive animals or intranasally immunized animals. Two hundred microliters pooled serum was injected i.v. into naive mice 4 h before challenge.

**Real-time PCR**

Uterine and lung CD45.2$^+$ cells were sorted from tissue single-cell suspensions by magnetic columns (Miltenyi Biotec) and resuspended in TRizol (Invitrogen). RNA was isolated using a RNAeasy mini kit (Qiagen) and then diluted to 4 ng/μl. Primers for chemokine receptors were CXCX3 forward, 5′-GCCCCCTCACCCTGATGGTG-3′, reverse, 5′-ATTCGCCCGATGGATGTT-3′; CCR5 forward, 5′-CGAAAACACATGATCAAGCG-3′, reverse, 5′-GTTCCTCTGTTGAGCGTAGGA-3′; and GAPDH forward, 5′-GGTGGCTGATGGATGTCGGA-3′, reverse, 5′-CGGAGATGATGACCTTCTTG-3′. Real-time PCR was conducted using the Quantitect SYBR Green RT-PCR kit (Qiagen) on an ABI Prism 7000 sequence detection system (Applied Biosystems, Carlsbad, CA). The data were analyzed using the ΔΔC<sub>m</sub> method, and expression of all genes was normalized against GAPDH. Fold induction was calculated based on expression of uninfected tissue.

**Quantitative PCR**

The levels of *C. trachomatis* in the tissue were quantified using a previously described quantitative PCR assay (35). Briefly, total nucleic acid from tissue homogenates was prepared using the QIAamp DNA mini kit (Qiagen). *Chlamydia* 16S DNA and mouse GAPDH DNA content was quantified using primer pairs and dual-labeled probes (IDT, San Jose, CA, or Applied Biosystems).

**Statistical analysis**

A two-tailed Mann-Whitney U test was applied to determine the statistical significance for bacterial burden among groups. All other data were evaluated with an unpaired two-tailed t test. A p value <0.05 was considered statistically significant. Representative results from at least two experiments are shown as means ± SE.

**Results**

*C. trachomatis* infects the lungs of mice and stimulates a potent immune response

To characterize *C. trachomatis* replication in the lungs of C57BL/6 (wild-type [wt]) mice following intranasal inoculation, we first inoculated mice with 10<sup>6</sup> IFU *C. trachomatis*, a dose that efficiently infects uterine tissues (29). Three days postinoculation (p.i.), some mice showed symptoms such as ruffled fur and diminished responsiveness. By day 11 p.i., 70% of inoculated mice succumbed to *C. trachomatis* infection (data not shown). When we inoculated mice intranasally with 10<sup>6</sup> IFU *C. trachomatis*, none of the present study, we explore the signals mediating homing of T cells to another mucosal site, the respiratory tract, and show that cross-mucosal protection can be induced in the genital tract through IFN-γ secreted by not only CD4$^+$ T cells but also by CD8$^+$ T cells.
the mice showed signs of disease. In these mice, *C. trachomatis* replicated in the lungs during the first 3 d p.i., but bacterial burden declined to below the limit of detection by day 14 (Fig. 1A). We then determined whether intranasal infection disseminated to the lymphatic tissues or other organs by measuring bacterial burden in the blood, spleen, liver, stomach, uterus, and lymph nodes of infected mice. We detected almost no *C. trachomatis* 16S DNA in these organs, except for some minimal levels in the mediastinal lymph node on day 3 but not on day 5 (Fig. 1B, 1C). This might be due to active Ag presentation in the lymph nodes draining the lung. Taken together, these data indicate that intranasal infection of *C. trachomatis* is mostly restricted to the respiratory tract and does not seem to replicate or spread to other organs.

To further characterize the immune response after intranasal inoculation, we examined the recruitment of inflammatory cells to the lungs. Recruitment of neutrophils to the lungs peaked on day 3 p.i.; macrophage and dendritic cell numbers peaked on day 5 p.i. and declined thereafter (Fig. 1D), indicating an active myeloid-lineage cell infiltration. Both CD4+ and CD8+ T cell numbers peaked on day 14 p.i in the lungs (Fig. 1E). To assess the infiltration of *C. trachomatis*-specific CD4+ T cells into the lungs, we transferred *C. trachomatis*-specific CD4+ TCR transgenic T cells (NR1) into naive mice and challenged these mice intranasally. NR1 cell numbers in the mediastinal lymph nodes peaked around day 5 p.i. (Fig. 1F). Similar to bulk CD4+ T cells, pathogen-specific CD4+ T cells peaked on day 14 p.i. in the lungs (Fig. 1F). Overall, these data indicate that *C. trachomatis* can infect the respiratory tract and induce an immune response that controls the infection.

*Intranasal immunization with C. trachomatis confers protection against secondary challenge in the genital tract*

To determine whether intranasal infection confers protection against secondary intranasal infection, we rechallenged intranasally inoculated mice a month later in the lung. These mice demonstrated significantly less *C. trachomatis* burden in their lungs than did nonimmunized mice (Fig. 2A), indicating that intranasal infection conferred protection against secondary challenge in the same tissue. We then examined whether intranasal immunization confers cross-mucosal protection against *C. trachomatis* genital infection. Three and 6 d after secondary transcervical infection, intranasally immunized mice had less *C. trachomatis* burden than did nonimmunized mice (Fig. 2B), indicating that intranasal immunization conferred cross-mucosal protection against genital infection. To determine whether a lower intranasal immunization dose would be sufficient to confer cross-mucosal protection, we immunized mice intranasally with 10⁵, 10⁴, 10³, and 10 IFU *C. trachomatis*. Five days after secondary challenge, all the intranasally immunized mice had significantly less bacterial burden than did the nonimmunized mice (Fig. 2C). Taken together, these data indicate that intranasal immunization of *C. trachomatis*, with as few as 10 IFU, confers protection against genital infection.

Abs are not necessary for cross-mucosal protection against *C. trachomatis*

It has been shown that in B cell–deficient (μMT) mice, *Chlamydia muridarum* clearance after secondary vaginal challenge is slightly delayed (21, 36). Furthermore, previous studies have demonstrated that the cross-mucosal protection against *C. muridarum* genital tract infection following intranasal immunization is associated with elevated Ab titers (12, 37). To test whether the cross-mucosal protection is Ab-dependent, intranasally immunized wt and μMT mice were rechallenged transcervically with *C. trachomatis*. Interestingly, both wt and μMT mice had lower bacterial burden in their uteri than did nonimmunized mice (Fig. 3A), demonstrating that mature B cells are not required for cross-mucosal protection. To further confirm these results, we transferred serum from intranasally immunized mice into naive mice

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**FIGURE 1.** *C. trachomatis* replicates in the lungs and induces an effective immune response. Groups of five C57BL/6 mice were intranasally infected with *C. trachomatis*. (A) On the indicated days p.i., bacterial burden in the lungs was determined by quantitative PCR. (B) On day 3 and (C) day 5 p.i., bacterial burden was determined in the indicated organs by quantitative PCR. (D) Absolute numbers of neutrophils (Gr1hiCD11bhi), macrophages (CD11b+F4/80⁺), dendritic cells (CD11c⁺MHC class II⁺), (E) CD4⁺ T cells (CD4⁺CD3⁺NK1.1⁻), and CD8⁺ T cells (CD8⁺CD3⁺NK1.1⁻) in the lungs were determined by flow cytometry. (F) *Chlamydia*-specific CD90.1⁺ NR1 CD4⁺T cells were transferred into CD90.2⁺ mice 1 d prior to intranasal infection. On the indicated days p.i., the numbers of NR1 CD4⁺ T cells in the lungs, mediastinal lymph nodes, and iliac lymph nodes were determined by flow cytometry.
This, CD4+ or CD8+ T cells were isolated from intranasally immunized mice and either CD4+ or CD8+ T cells are sufficient to confer cross-mucosal protection. To test this, we treated intranasally immunized mice with isotype control Abs or Abs to deplete CD4+ or CD8+ T cells both before and throughout the transcervical challenge. Surprisingly, CD4+ T cell–depleted mice remained protected against C. trachomatis (Fig. 4A). These results suggested that unlike priming in the genital tract, priming in the respiratory tract stimulates a protective T cell response in the genital mucosa that is independent of CD4+ T cells. Because IFN-γ plays a pivotal role in C. trachomatis growth restriction and both CD4+ T and CD8+ T cells in the uteri are independently capable of producing IFN-γ (Fig. 4B, 4C), it was possible that CD8+ T cells were compensating for the lack of CD4+ T cells and mediating cross-mucosal protection. To test this, mice were primed intranasally and treated with neutralizing Abs for both CD4+ and CD8+ T cells. These data are representative of two independent experiments. *p ≤ 0.05, **p ≤ 0.01.

Before transcervical challenge, similar levels of C. trachomatis were detected in mice that received immune serum versus naive serum (Fig. 3B), indicating that immune serum from intranasally immunized mice is not sufficient to confer cross-mucosal protection. Taken together, these data showed that B cells did not mediate the cross-mucosal protection against C. trachomatis.

T cells are required for cross-mucosal protection against C. trachomatis, and either CD4+ or CD8+ T cells are sufficient

Because CD4+ T cells are required and sufficient for protection against C. trachomatis rechallenge in the uterus (29), we hypothesized that CD4+ T cells might also be responsible for the cross-mucosal protection. To test this, we treated intranasally immunized mice with isotype control Abs or Abs to deplete CD4+ T cells both before and throughout the transcervical challenge. Interestingly, CD4+ T cell–depleted mice remained protected against C. trachomatis (Fig. 4A). These results suggested that unlike priming in the genital tract, priming in the respiratory tract stimulates a protective T cell response in the genital mucosa that is independent of CD4+ T cells. Because IFN-γ plays a pivotal role in C. trachomatis growth restriction and both CD4+ T and CD8+ T cells in the uteri are independently capable of producing IFN-γ (Fig. 4B, 4C), it was possible that CD8+ T cells were compensating for the lack of CD4+ T cells and mediating cross-mucosal protection. To test this, mice were primed intranasally and treated with neutralizing Abs for both CD4+ and CD8+ T cells. These mice had significantly more C. trachomatis burden compared with isotype control–treated mice (Fig. 4A), indicating that a T cell population was required for the cross-mucosal protection against C. trachomatis.

Because mice that received CD4+ or CD8+ T cell depletion treatment but not both were protected against secondary genital challenge (Fig. 4A), we hypothesized that CD4+ or CD8+ T cells alone are sufficient to confer cross-mucosal protection. To test this, CD4+ or CD8+ T cells were isolated from intranasally immunized mice and naive mice, CFSE labeled, and transferred into naive hosts 4 h before C. trachomatis transcervical challenge. We observed a significant reduction of C. trachomatis burden in mice that received immune but not naive CD4+ or CD8+ T cells compared with control mice that did not receive any T cells (primary) (Fig. 4D). These data indicate that CD4+ or CD8+ T cells alone from intranasally primed mice are sufficient to mediate protection, and this protection is not simply due to increased T cell numbers because naive T cells have no protective effect (Fig. 4D). Similar numbers of naive and immune T cells were recovered from draining lymph nodes (data not shown), and a similar proportion of naive and immune T cells in the lymph nodes proliferated as indicated by CFSE dilution (data not shown). Interestingly, significantly more intranasally primed CD4+ or CD8+ T cells reached the upper genital tract (Fig. 4E) and were actively proliferating compared with naive T cells (Fig. 4F). These results suggest that intranasal immunization enables both CD4+ T cells and CD8+ T cells to more efficiently enter the upper genital tract and engage in proliferation and protection. Additionally, when mice were...

**FIGURE 3.** Mature B cells are not necessary for cross-mucosal protection against C. trachomatis. (A) Groups of seven to eight C57BL/6 and μMT mice were intranasally immunized with C. trachomatis. Four weeks after immunization, these mice, naive C57BL/6, and naive μMT mice were challenged in the genital tract. Five days later, bacterial burden was determined by quantitative PCR. (B) Groups of seven to eight C57BL/6 mice were intranasally immunized. Four weeks later, serum was extracted from peripheral blood of these mice and naive mice. Immune or naive sera were injected i.v. into naive mice. These mice were then infected in the genital tract and 5 d later bacterial burden was determined by quantitative PCR. These data are representative of two independent experiments. *p ≤ 0.05.
immunized in the respiratory tract with a lower dose (100 IFU), immune CD4+ or CD8+ T cells were still sufficient to confer protection against transcriptional infection (data not shown).

Based on previous T cell depletion and transfer studies, CD8+ T cells from mice immunized in the genital tract with *C. trachomatis* were not required or sufficient to confer protection (27, 29). However, as shown in the present study, CD8+ T cells from *C. trachomatis* intranasally primed mice are sufficient to confer protection (Fig. 4D). As a first step toward understanding the differential protective phenotypes of transversely versus intranasally primed CD8+ T cells, we compared the ability of immune CD8+ T cells primed transversely or intranasally to migrate to the genital mucosa and proliferate in a sensitive cotransfer experiment (Fig. 5A). CD8+ T cells were isolated from SLOs of CD90.1+/CD45.2+ transversely or CD90.2+/CD45.2+ intranasally primed mice, CFSE labeled, and mixed 1:1 before transfer into CD45.1+ hosts, which were then transversely infected. A control group received 1:1 mixture of intranasally primed and transversely primed CD8+ T cells. Five days p.i., we recovered similar numbers of intranasally primed and transversely primed T cells from all examined organs (Fig. 5B). These results suggested that T cells from SLOs of intranasally primed and transversely primed donors have a similar ability to migrate to the genital tract following transversely infection. A similar proportion of CD4+ T cells from transversely primed or intranasally primed donors proliferated (CFSEdim) and was able to secrete IFN-γ (Fig. 5C, 5D). Interestingly, significantly more intranasally primed CD8+ T cells proliferated and secreted IFN-γ compared with their transversely primed counterparts (Fig. 5C, 5D). These results suggest that compared with transversely priming, intranasal priming engages a larger proportion of CD8+ T cells to proliferate and secrete IFN-γ in response to transversely *C. trachomatis* infection. When we compared *C. trachomatis*-specific memory CD8+ T cells primed either intranasally or transversely, we observed an enrichment of effector memory T (Tem; CD127−CD62Lhigh) cells in intranasally primed CD8+ T cells when compared with transversely primed CD8+ T cells (Fig. 5E, 5F). Because Tem cells are thought to provide immediate effector function at the portal of pathogen entry (38), the downregulation of CD62L on intranasally primed pathogen-specific memory CD8+ T cells might contribute to their better effector function and superior protective capacity upon secondary challenge in the distal mucosa.

CXCR3 and CCR5 are dispensable for cross-mucosal protection against *C. trachomatis*

A previous study from our laboratory has shown that CXCR3 and CCR5 cooperatively direct *Chlamydia*-specific CD4+ T cells into the genital mucosa (30). Interestingly, CXCR3 but not CCR5 directs Ag-specific CD4+ T cells into the lungs during parainfluenza virus infection (39). To determine whether CXCR3 and CCR5 contribute to T cell homing during *C. trachomatis* intranasal infection and whether they are involved in cross-mucosal protection, we tested whether CXCR3 and CCR5 are upregulated on leukocytes during *C. trachomatis* nasal infection and whether they are involved in cross-mucosal protection, we tested whether CXCR3 and CCR5 are upregulated on leukocytes during *C. trachomatis* respiratory tract infection. Consistent with the previous study, both CXCR3 and CCR5 were upregulated on uterine leukocytes following *C. trachomatis* genital infection (Fig. 6A). In contrast, only CCR5 but not CXCR3 expression was induced on lung leukocytes following *C. trachomatis* infection (Fig. 6A). We did not observe significant upregulation of other chemokine receptors, including CCR4, which was recently identified to be involved in lung-homing of T cells (data not shown) (40). To determine whether CCR5 contributes to the homing of *C. trachomatis*-specific CD4+ T cells to
the lungs during intranasal infection, we conducted a sensitive competitive homing assay that monitors the ability of wt and chemokine receptor–deficient transgenic T cells to home to the lungs under the same conditions. We transferred a 1:1 mixture of NR1 T cells from wt and chemokine receptor–deficient transgenic mice before intranasal infection. At the peak of T cell recruitment, we determined the migration index of the transferred T cells in the lungs. Statistically, the migration index was 1 in the spleens. However, in the lungs, the migration indices of both CCR5$^{−/−}$ and CXCR3$^{−/−}$ CCR5$^{−/−}$ NR1 T cells were significantly $< 1$ (Fig. 6B), indicating that CCR5 contributes to the homing of C. trachomatis–specific CD4$^{+}$ T cells into the lungs. Moreover, because the migration index of CCR5$^{−/−}$ and CCR5$^{−/−}$ CXCR3$^{−/−}$ T cells was similar, CXCR3 does not seem to have an additive or antagonistic impact on the contribution of CCR5 to T cell trafficking. Although CCR5 contributes to the migration of C. trachomatis–specific CD4$^{+}$ T cells into the lungs during C. trachomatis respiratory infection, CCR5$^{−/−}$ and CXCR3$^{−/−}$ CCR5$^{−/−}$ mice had similar bacterial burden in their lungs compared with wt mice (Fig. 6C), suggesting that these chemokine receptors are not required for C. trachomatis clearance in the lungs.
Because CXCR3 and CCR5 are required for T cell–mediated protection against *C. trachomatis* primary transcervical infection (30), we examined whether these chemokine receptors are also involved in cross-mucosal protective immunity. To test this, intranasally immunized wt and CXCR3<sup>−/−</sup>CCR5<sup>−/−</sup> mice were subsequently challenged in the genital tract. These mice were all protected against genital challenge (Fig. 6D), indicating that CXCR3 and CCR5 are dispensable for cross-mucosal protection against *C. trachomatis*. Although chemokine receptor–deficient mice efficiently produced *C. trachomatis* transmucosal burden following intranasal immunization, it is still possible that only one of the T cell populations requires these chemokine receptors to mediate cross-mucosal protection considering that CD4<sup>+</sup> or CD8<sup>+</sup> T cells alone are sufficient to mediate protection (Fig. 4D). To address this, we transferred CD4<sup>+</sup> and CD8<sup>+</sup> T cells from intranasally immunized wt and CXCR3<sup>−/−</sup>CCR5<sup>−/−</sup> mice into naive hosts before transcervical challenge. Five days after challenge, transferred CXCR3<sup>−/−</sup>CCR5<sup>−/−</sup>CD4<sup>+</sup> and CD8<sup>+</sup> T cells migrated to the genital tract and proliferated as efficiently as did wt T cells (data not shown). Similar to wt CD4<sup>+</sup> and CD8<sup>+</sup> T cells, transferred CXCR3<sup>−/−</sup>CCR5<sup>−/−</sup>CD4<sup>+</sup> and CD8<sup>+</sup> T cells conferred cross-mucosal protection (Fig. 6E). Taken together, these data suggest that CD4<sup>+</sup> and CD8<sup>+</sup> T cells mediate cross-mucosal protective immunity against *C. trachomatis* in a CXCR3- and CCR5-independent manner.

To determine whether chemokine receptors other than CXCR3 and CCR5 contribute to the ability of intranasally primed T cells to mediate cross-mucosal protection, we isolated T cells from intranasally immunized mice and treated these cells with Ptx to block Gi receptor–coupled signaling downstream of most chemokine receptors.
receptors. Treated or untreated immune T cells were transferred into naïve mice, which were then challenged transcervically with *C. trachomatis*. Because Ptx treatment efficiently blocks G<sub>i</sub> receptor–coupled signaling for 3 d (34), we determined the number of transferred T cells and bacterial burden 3 d after transcervical challenge. We recovered almost no Ptx-treated donor cells in the draining lymph nodes, suggesting that the ex vivo Ptx treatment was efficient in blocking the chemokine receptor signaling necessary for T cell trafficking to the lymph nodes (Fig. 6F). Although the accumulation of treated cells in the uterine tissues was not statistically different from the accumulation of untreated cells, we did observe a trend toward fewer Ptx-treated cells than untreated cells (Fig. 6F), suggesting that a Ptx-sensitive chemokine receptor might contribute to the trafficking of intranasally primed T cell into genital mucosa. Moreover, mice that received Ptx-treated T cells were no longer protected against *C. trachomatis* challenge in the genital tract (Fig. 6G), indicating that some Ptx-sensitive G<sub>i</sub> receptor–coupled signaling is required for cross-mucosal protection.

### IFN-γ produced by CD4<sup>+</sup> and CD8<sup>+</sup> T cells is required for cross-mucosal protection against *C. trachomatis*

Because IFN-γ plays a key role in controlling *Chlamydia* genital infection and activated CD4<sup>+</sup> and CD8<sup>+</sup> T cells are both potent producers of IFN-γ (24–26, 41), we hypothesized that IFN-γ produced by intranasally primed T cells is responsible for cross-mucosal protection. To test this, we immunized wt and IFN-γ<sup>−/−</sup> mice intranasally with 100 IFU *C. trachomatis* and then challenged these mice transcervically. We chose this immunization dose because IFN-γ<sup>−/−</sup> mice survive this challenge dose and yet this dose is sufficient to confer protection in the wt mice (Fig. 2C).

**FIGURE 7.** T cell–mediated cross-mucosal protection against *C. trachomatis* is dependent on IFN-γ. (A) Groups of 6–10 C57BL/6 and IFN-γ<sup>−/−</sup> mice were intranasally immunized with 100 IFU *C. trachomatis*. A month later, these mice and naïve mice were challenged in the genital tract. Bacterial burden was determined 3 d after challenge by quantitative PCR. (B) Groups of 9–10 C57BL/6 mice were intranasally immunized with *C. trachomatis*. A month later, these mice and naïve mice were treated with IFN-γ–neutralizing or isotype control Abs and then challenged in the genital tract. Bacterial burden was determined by quantitative PCR 5 d after challenge. (C–F) Groups of 19–20 CD90.1<sup>+</sup> mice were intranasally immunized with *C. trachomatis*. A month later, CD4<sup>+</sup> or CD8<sup>+</sup> T cells were purified from their SLOs, labeled with CFSE, and transferred into CD90.2<sup>−/−</sup> wt or IFN-γR<sup>−/−</sup> mice. These mice and control mice that did not receive any T cells were then challenged in the genital tract. Five days later, (C) bacterial burden was determined by quantitative PCR. (D) Absolute number of donor cells, identified as CD90.1<sup>+</sup>CD4<sup>+</sup> or CD90.1<sup>+</sup>CD8<sup>+</sup>. (E) percentage of donor cells that were CFSE<sup>dim</sup>, and (F) IFN-γ mean fluorescence intensity (MFI) of donor cells in the uterine tissues were determined by intracellular staining and flow cytometry. These data are representative of two independent experiments. *p ≤ 0.05, **p ≤ 0.01.
produced by intranasally primed CD4+ and CD8+ T cells is required for cross-mucosal protection against genital C. trachomatis infection.

**Discussion**

Ab response–associated cross-mucosal protection is well documented (10, 12, 13). In this study, we took advantage of the ability of C. trachomatis to infect both the murine respiratory and genital tracts to ask whether cross-mucosal protection can be elicited using a pathogen where protection is mainly T cell mediated. Our findings demonstrate that intranasal immunization with C. trachomatis induces cross-mucosal protection against a subsequent transcervical challenge. Although we cannot completely rule out the role of B cells in fine-tuning this process, Abs are dispensable for the cross-mucosal protection against transcurrent C. trachomatis infection. In contrast, T cells are necessary for cross-mucosal protection. Moreover, either CD4+ T cells or CD8+ T cells are sufficient to mediate this protection through IFN-γ secretion. Although a previous report has shown that TNF-α secreted by CD8+ T cells contributes to pathology in mice intravaginally inoculated with C. muridarum (42), and we did observe TNF-α production by CD8+ T cells, we did not observe increased pathology 30 d following secondary genital challenge with C. trachomatis (data not shown).

Previous studies have shown that intranasal immunization with either adjuvanted Chlamydia proteins or live bacteria confers protection against a genital challenge, and that protection was correlated with heightened Ab titers and IFN-γ secretion (12, 37, 43). However, none of these studies tested specifically which arm of the adaptive immune system (Abs or T cells) is required or sufficient for the cross-mucosal protection. Only with our experiments using neutralizing reagents specifically during secondary challenge and T cell transfer into IFN-γ-deficient animals can we clearly demonstrate the requirement and sufficiency of T cell–secreted IFN-γ for cross-mucosal protection. The obvious question arises as to what enables intranasally primed T cells to mediate protection in the genital tract. The upper genital tract and lower respiratory tract resemble the liver and CNS where even commensal bacteria cannot be tolerated. Moreover, in contrast to the gut mucosa, the uterus and lung lack organized lymphoid elements in healthy individuals (44–46). Therefore, the induction of immunity to the respiratory and genital tract by pathogens must occur outside of the tissue followed by recruitment of recirculating cells into infected sites. Previous studies have shown that T cells activated through systemic or mucosal vaccination have the capacity to traffic widely to mucosal tissues and differentiate into protective memory T cells (38, 47–49). However, these studies used viral vaccines that were either given systemically or later disseminated systemically. This suggests that Ag spread might be critical in these cases to form protective T cell populations across mucosal sites. Although the L2 serotype of C. trachomatis used in this study has the ability to spread via the lymphatic system to draining lymph nodes in humans (50), we detected almost no C. trachomatis 16S DNA in systemic organs or lymph nodes of intranasally challenged mice. We did detect minimal levels of C. trachomatis 16S DNA in the lung-draining lymph nodes on day 3 p.i. but not later. However, we think that this is due to APCs transiently carrying bacterial Ags to the local lymph nodes. This suggests that systemic spread might not be required for the cross-mucosal protection observed in our study. There have been previous studies showing that CD8+ T cell responses induced in one tissue can bridge different mucosal compartments. For instance, oral rotavirus infection, Sendai virus lung infection, and Listeria monocytogenes oral infection all result in pathogen-specific CD8+ T cells detectable at nonlymphoid sites beyond the initial site of Ag encounter (49). These and our observations suggest that the anatomic site of initial T cell activation may not predict the subsequent tissue-specific migration of these T cells. Therefore Ag-experienced T cells that disseminate systemically might not only protect against systemic spread of the primary infection but also may serve as key sentinels, protecting distant mucosal surfaces against secondary infection.

The ability of C. trachomatis to efficiently replicate in both the lung and uterus allowed us to study the tissue-specific contribution of chemokine signaling to the migration of clonal T cell populations in the context of the same pathogen challenge. Although both CXCR3 and CCR5 are upregulated on uterine leukocytes during C. trachomatis genital infection (30), only CCR5 is upregulated on leukocytes during C. trachomatis lung infection. CCR5 contributes to C. trachomatis–specific CD8+ T cell trafficking to the lung, but it seems to be dispensable for the accumulation of C. trachomatis–specific CD8+ T cells in the lung (data not shown). Nevertheless, the CCR5−/− and CXCR3−/− CCR5−/− T cells that migrate to the lungs are sufficient to reduce C. trachomatis burden at similar rates to wt T cells. This is different from influenza virus lung infection where CXCR3 deficiency rescues the lethal infection in CCR5−/− mice caused by phagocyte-mediated immunopathology (51). This is also different from genital C. trachomatis infection where both CXCR3 and CCR5 are required for pathogen-specific CD4+ T cell recruitment and efficient bacterial clearance (30). Overall, these observations suggest that both tissue-specific and pathogen-specific factors may result in the different chemokines signals mediating migration to different infected tissues. Intranasally primed memory CD4+ or CD8+ T cells do not require CXCR3 or CCR5 to migrate to the upper genital tract. Ptx-sensitive chemokine receptors are required for intranasally primed memory CD4+ and CD8+ T cells to confer protection in the genital tract. Ptx-treated donor CD4+ or CD8+ cells were completely absent from the lymph nodes draining the genital tract. Therefore, lymph node priming guided by Ptx-sensitive chemokine receptor(s), possibly CCR7, seems to be necessary for the T cells to mediate protection. Future studies will focus on delineating the exact G1-coupled receptor signaling critical for the protective capacity of intranasally primed T cells against genital tract infection.

Although it is well accepted that CD4+ T cells are both necessary and sufficient for secondary protection against C. trachomatis genital tract infection (20, 28, 29), previous studies have demonstrated that a number of C. trachomatis Ags gain access to the host cell cytosol where they can also stimulate CD8+ T cells (33, 52). Moreover, transfer of CD8+ T cell lines specific for these Ags or immunization with a recombinant virus expressing these Ags provides protection (33). Intriguingly, for a pathogen that replicates primarily in epithelial cells that express MHC class I but not high levels of MHC class II, a protective CD8+ T cell response does not seem to develop during natural genital infection. However, we showed that priming in the respiratory tract stimulates a CD8+ T cell population that is sufficient for cross-mucosal protection in the genital tract. These observations suggest that some tissue-specific factors may contribute to differential priming outcomes of CD8+ T cells. Previous studies on the differential impact of IL-17 on Th1 immune responses and C. muridarum clearance in the respiratory tract versus genital tract are consistent with this concept (53, 54). Because dendritic cells are key to priming T cells, it is possible that differential expression of stimulatory and/or inhibitory molecules on these tissue-specific dendritic cells may affect priming and/or memory development of CD8+ T cells. For instance, we observed lower programmed death ligand 1 (PD-L1) expression on
lungs, dendritic cells from intranasally primed mice as compared with PD-L1 expression on uterine dendritic cells from mice primed transcutaneously (data not shown). PD-1/PD-L1 signaling has been shown to hinder the CD8+ T cell response, specifically T_{en} cell formation, following C. trachomatis infection in the genital tract (27). Because the lower PD-L1 induction in the lungs correlates with an enrichment of T_{en} cells in the SLOs of intranasally primed mice and their superior protective capacity, we speculate that differential induction of PD-1/PD-L1 signaling might contribute to the differential priming outcomes in the lung and in the genital tract. This hypothesis will be tested in future studies where we will also compare dendritic cell populations and other factors that might be involved in CD8+ T cell priming at these two mucosal surfaces. These studies will shed light on what factors are critical for shaping protective CD8+ T cell responses to C. trachomatis and other human pathogens that depend on CD8+ T cells for protection.

C. trachomatis and other sexually transmitted pathogens are a worldwide public health concern. Vaccines against these pathogens would significantly reduce the reproductive damage caused by these organisms. This study demonstrates that intranasal immunization with C. trachomatis can confer cross-mucosal protection against genital infection, showing that T cell–mediated cross-mucosal protection can be induced. Our findings provide proof of concept that intranasal immunization can be used as a route of immunization for genital pathogens that depend on T cells for protection, such as C. trachomatis and HIV.

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Disclosures

The authors have no conflicts of interest.

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