

A Novel LNP-Based *Chlamydia* Subunit Vaccine Formulation That Induces Th1 Responses without Upregulating IL-17 Provides Equivalent Protection in Mice as Formulations That Induced IL-17 and Th1 Cytokines

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Abstract

We evaluated novel Chlamydial vaccines, consisting of major outer membrane protein (MOMP) alone or in combination with polymorphic membrane proteins D (PmpD) and G (PmpG) using a C57BL/6 mouse model. Native MOMP (nMOMP) isolated from *C. muridarum* elementary bodies (EBs) and recombinant PmpD and PmpG proteins were adjuvanted with Monophosphoryl lipid A (MPLA), with either lipid nanoparticles (LNPs) or the cationic lipid dimethyldioctadecylammonium bromide (DDA). Antibody titers to *C. muridarum* nMOMP, and EBs were evaluated by ELISA, and T-cell responses were analyzed by intracellular cytokine staining (ICS). Protection from challenge was determined by qPCR. Vaccine immunized mice showed significantly higher antibody titers to nMOMP ($P < 0.001$) and *C. muridarum* EBs ($P < 0.001$), when compared to the adjuvant alone group. Antibody titers in vaccine groups with Monophosphoryl lipid A (MPLA) + LNP were higher as compared to the MPLA + DDA group ($P < 0.001$) except for (Cm nMOMP + PmpG + PmpD p73 + PmpD p82 + MPLA + DDA) vs (Cm nMOMP + PmpG + PmpD p73 + PmpD p82 + MPLA + LNP) for both *C. muridarum* EBs and PmpG. ICS analysis showed more robust CD4 + T-cell responses (IFN- γ /IL-2/TNF- α) in the DDA and LNP groups compared to the adjuvant alone group. The DDA + MPLA gave robust Th17 responses in comparison to MPLA and LNP group. Mice immunized with *Chlamydia* antigens also showed protection from *C. muridarum* challenge, by reduction in bacterial shedding for all groups ($P < 0.003$) compared to shedding from the adjuvant

control. Both vaccine formulations generated robust immunological responses, and both were protective by reducing bacterial shedding after challenge. This data indicates equal protection can be achieved without the induction of Th17 responses.

Keywords

LNP, *Chlamydia*, IL-17, Mouse Model, Th1 Cytokines

1. Introduction

Chlamydia infections cause substantial morbidity and socio-economic burden worldwide, and although antibiotic treatment is effective, the high rate of asymptomatic infections leads to chronic infections that may ultimately cause upper genital tract pathology. An efficacious vaccine could prevent the disease sequelae that are common following *Chlamydia* infections including infertility and ectopic pregnancy [1] [2] [3]. Each year approximately 1.4 million new cases of sexually transmitted *C. trachomatis* infections are diagnosed in the United States and approximately 113 million new cases are reported worldwide [2] [4]. Although *C. trachomatis* infection is responsive to antibiotic treatment, more than 70% of infections in women are asymptomatic [5], making both diagnosis and control of infection difficult. Therefore, there is a substantial need for an efficacious vaccine to protect against *Chlamydia* infection.

Chlamydia vaccine development has been decades long endeavor. In recent years encouraging progress has been made towards a native MOMP based vaccine with levels of protection approaching those of live EB vaccination in mice [6] [7] [8]. An antigen-based subunit vaccine, whether using native purified proteins or recombinantly expressed proteins appears as a practical path forward. Although MOMP is a promising vaccine target, additional antigens may need to be included to create an efficacious vaccine.

Recent vaccine studies using MOMP and Pmp combinations have shown promise as vaccine candidates with early clearance of *Chlamydia* infections compared with unvaccinated control groups [9] [10] [11]. The Pmp family of proteins are good T-cell antigens and potential targets for a T-cell focused vaccine [10] [12] [13]. MOMP has been shown to elicit a strong humoral immune response [14]. A vaccine that includes antigens that provides T-cell and antibody responses against *Chlamydia* may provide optimal protection against both initial and repeat infection than a vaccine profile that only elicits a Th1 or Th2 responses [10]. IL-17 mediated immunity has been shown to play a role in the control of intracellular pathogens, including *Chlamydia* [9] [15]. However, there is also evidence for a pathogenic role through enhanced recruitment of polymorphonuclear neutrophils and inflammatory monocytes in the upper genital tract (UGT). The Th17-mediated inflammation has been associated with tissue destruction, intra-abdominal adhesions and increases in splenic weights in the

mouse model [15] [16] [17]. We tested the role of Th1 and/or Th17 T-cells in affording protection from *Chlamydia* infection and their ability to cause pathology in the upper genital tract utilizing two vaccine formulations.

We have evaluated numerous conserved *Chlamydia* antigen targets (data not shown) with minimal protection or reduction in bacterial burden observed following immunization and intravaginal challenge from most targets. We have observed protection with vaccine formulations including nMOMP similar to what has been published in the literature [6] [7] [8]. Since MOMP is a good humoral antigen, we also looked for antigens that would elicit cell-mediated immune responses. Immunoproteomic vaccine studies found that four polymorphic membrane proteins (PmpE, PmpF, PmpG and PmpH) are immunodominant, recognized by various MHC class II haplotypes and are protective in mouse models [9] [10] [13]. PmpG/F have been shown to be the most immunodominant of the Pmps [10]. Therefore, based on protection with nMOMP observed in our laboratory and publications citing protective immunity for both MOMP and polymorphic membrane proteins, with PmpG/F being most immunodominant of the Pmps, we focused on nMOMP, PmpG, PmpD passenger domain (PmpD-p73) and PmpD translocator domain (PmpD-p82) as candidate vaccine antigens in the current study. Additionally, various adjuvants were included to drive the cell mediated immune response toward Th1, and/or Th17 and the role of T-helper population in conferring protection was evaluated. To determine the role of Th17 mediated immunity, vaccine formulations in some test groups were adjuvanted with the cationic lipid DDA which has been shown to induce potent Th1 and Th17 responses [18] whereas the lipid nanoparticles (LNP) formulations were used to bias toward Th1 responses. Immunogenicity was evaluated for both T-cell responses and antibody, and efficacy was determined by measuring the magnitude and duration of shedding of *Chlamydia* after an intravaginal challenge. The combination of DDA and MPLA gave robust Th17 responses in comparison to LNP and MPLA. Both sets of formulated antigens (MPLA + LNP or MPLA + DDA) resulted in robust antibody titers to nMOMP ($P < 0.001$) and *C. muridarum* EBs ($P < 0.001$), when compared to the adjuvant-alone control group. Immunized groups also showed protection from challenge with *C. muridarum*, as evidenced by a reduction in bacterial shedding from the vagina for all groups ($P < 0.003$) compared to shedding from the adjuvant control group. Taken together, the data suggest that the vaccines formulated with either MPLA + LNP or MPLA + DDA elicited strong immunological responses and both were protective by reducing bacterial shedding after challenge. Furthermore, equal protection is achieved with or without a Th17 response.

2. Methods

2.1. Ethics Statement

All animal experiments were approved by the Merck & Co., Inc., Kenilworth, NJ,

USA, Institutional Animal Care and Use Committee (IACUC). All procedures were performed in accordance with our institution's IACUC guidelines in strict accordance with the recommendations in the Guide for Care and Use of Laboratory Animals of the National Institutes of Health. Mice were housed in large mouse containers (n = 10 mice/box and n = 5 mice/box for ICS) with micro isolator lids, and the rooms were maintained with controlled humidity and temperature, and 12-hour light-dark cycles. All containers had nestlets and animals were provided standard chow (Purina 5001 rodent diet) and water ad libitum. The physical condition of the animals was monitored daily (7 days a week), and any health changes were noted. At the end of the study, animals were euthanized using CO₂ inhalation (10% - 30% CO₂ in the air mixture inhaled per minute). No animals were found to be moribund or to have any adverse events throughout the study.

2.2. Cell Culture and Propagation of *Chlamydia muridarum*

C. muridarum was obtained from Bernard Arulanandam (UTSA San Antonio, Texas). HeLa 229 cells were used for propagation of *C. muridarum*. HeLa 229 cells were grown in Eagle's Minimal Essential Medium (EMEM; ATCC, Manassas, VA) supplemented with 10% heat-inactivated fetal bovine serum (FBS; Hyclone, Logan, UT), 50 µg/ml vancomycin (Sigma, St. Louis, MO), and 10 µg/ml gentamicin (Gibco; Carlsbad, CA). Host cells were seeded into tissue culture flasks at a cell density of 5×10^5 cells/ml and incubated overnight at 37°C in 5% CO₂ to achieve a confluent monolayer. Cell monolayers were infected with a *Chlamydia* stock diluted in sucrose-phosphate-glutamate (SPG) buffer. The *C. muridarum* strain was cultured for 48 hours. The *Chlamydiae* were harvested from the infected cells and purified by centrifugation through 30% Renografin (Bracco Diagnostics, Princeton, NJ) and stored frozen at -80°C. All Chlamydia IFU titers used to calculate immunization and challenge doses were determined by tissue culture methods.

2.3. *Chlamydia* Recombinant Proteins

The recombinant *Chlamydia* proteins were cloned, expressed and purified as follows: PmpG (amino acids 25 - 500), PmpD passenger domain (p73) (amino acids 53 - 757) and PmpD translocator domain (p82) (amino acids 758 - 1520) as described by Swanson [19]; *C. muridarum* gene sequences were synthesized by Geneart (Thermo Fisher, Germany) and cloned into pET30a and pET28a vectors (Novagen, Cambridge, MA), respectively, using standard molecular biology techniques. Plasmids containing the genes were transformed into the *Escherichia coli* strain BL21 (DE3) (New England Biolabs, Ipswich, MA) with protein expression induced using the lac promoter for T7 RNA expression using isopropyl-β-D-thiogalactopyranoside (IPTG).

2.4. Purification of His-Tagged PmpG, PmpD-p73 and PmpD-p82

Cell pellets of *E. coli* expressing PmpG, PmpD-p73 or PmpD-p82 were resus-

pended in lysis buffer (50 mM TRIS, pH 8.0, 300 mM NaCl, and 1X protease inhibitors (Roche, Basel, Switzerland, EDTA free), and lysed with three passes through a microfluidizer (Microfluidics M-110P) at 15,000 psi. The lysate was clarified by centrifugation (~19,000 ×g) and the pellet (containing inclusion bodies) was solubilized in a urea buffer (8M urea, 10 mM MES pH 6.5, 150 mM NaCl, and 20 mM Imidazole) and clarified by ultracentrifugation (~160,000 ×g). The solubilized fraction was purified while in urea by immobilized metal affinity chromatography (IMAC) with Ni NTA agarose and step eluted with 200 mM imidazole. The IMAC product was refolded using extensive dialysis against 10 mM MES pH 7.3, 150 mM NaCl containing 0.1% Zwittergent, 3 - 14 (PmpD-p73 and PmpD-p82) or phosphate buffered saline (PBS) containing 0.1% Zwittergent, 3 - 14 (PmpG) using a Pierce Slide-A-Lyzer (Pierce, Rockford, Illinois). Cassette with a 10 kDa MWCO while step reducing the urea concentration to zero. The PmpD-p73 and PmpD-p82 in the MES buffered saline containing 0.1% Zwittergent, 3 - 14 or the PmpG in the PBS containing 0.1% Zwittergent, 3 - 14 were used in both *in vitro* and *in vivo* studies. The final products were sterile filtered, and the concentration was determined by amino acid analysis. Purity of the final product was evaluated by SDS-PAGE and by in-solution enzymatic digestion with 1D/LC-MS-MS analysis.

2.5. Amino Acid Analysis

Vapor phase hydrolysis was performed with constant boiling 6 N HCl at 150°C for 1 hour using an ELDEX (Napa, CA) H/D workstation. Protein hydrolysates and amino acid standards were derivatized with 6-aminoquinolyl-N-hydroxysuccinimidyl carbamate (AQC) using the Waters AccQ Tag Ultra derivatization kit according to the manufacturer's protocol. AQC reacts with primary and secondary amines to form stable fluorescent derivatives that can be separated by RP-HPLC. The fluorescent AQC derivatives were separated on an AccQ Tag Ultra C18, 1.7 μm, 2.1 × 100 mM column using a modified gradient program.

2.6. Native MOMP Purification from Infected Cells (HeLa)

Native MOMP (nMOMP) was purified by extraction using sonication of intact *Chlamydia*-infected HeLa cells based on a method by de La Maza [8] with modifications to infected cell starting material, less frequent sonication, and altered chromatography. The initial steps used phosphate buffer with CHAPS and 100 mM DTT and subsequently a phosphate buffer containing Zwittergent, 3 - 14 with 100 mM DTT. The MOMP was further purified post-extraction with hydroxyapatite chromatography. The hydroxyapatite product was concentrated using tangential flow filtration (TFF), and then purified with anion exchange chromatography. The nMOMP was dialyzed into 10 mM MES pH 7.3, 150 mM NaCl, and 0.1% Zwittergent, 3 - 14 for use in animal dosing and *in vitro* studies.

2.7. Murine Model and Specimen Collection

Female C57BL/6 mice were purchased from Taconic Farms (Hudson, NY). At the time of study initiation, mice were 6 - 7 weeks of age, with food and water provided *ad libitum*. Animals were randomly assigned to cages upon receipt from the vendor. Animals were treated and assessed in numerical order groups 1 - 8. Study design is shown in **Figure 1**. Fifteen animals per group (10 for challenge and 5 for ICS) were immunized by subcutaneous (s.c.) route with the following combinations of adjuvants and antigens as seen in **Table 1**: Group 1) MPLA + DDA + LNP (adjuvant control, no vaccine group), Group 2) Cm nMOMP + MPLA + DDA, Group 3) Cm nMOMP + MPLA + LNP, Group 4) Cm nMOMP + PmpG + MPLA + DDA, Group 5) Cm nMOMP + PmpG + MPLA + LNP, Group 6) Cm nMOMP + PmpG + PmpD p73 + PmpD p82 + MPLA + DDA, Group 7) Cm nMOMP + PmpG + PmpD p73 + PmpD p82 + MPLA + LNP, Group 8) Live Cm EB (positive control) were immunized with 1×10^6 EB in SPG per mouse by intraperitoneal (i.p.) route.

Blood was obtained via tail-vein on days—1 and day 42. Immunizations were performed on days 0, 20, 30. Spleens were harvested on day 40 from 5 mice per group. Mice were rested for 1 month prior to intravaginal challenge. Progesterone [medroxyprogesterone acetate (Depo-Provera; Pfizer; New York, NY)] was

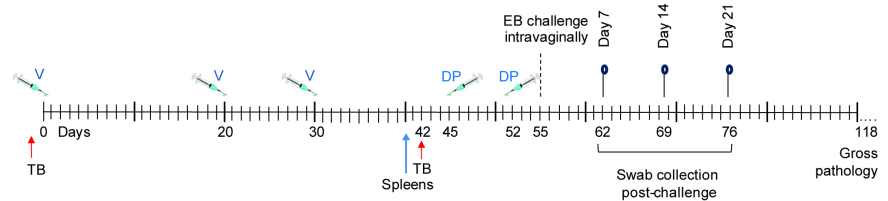


Figure 1. Study design. Schedule of vaccination, collection of spleens, *Chlamydia muridarum* challenge, cervicovaginal swabbing, and gross pathology in female C57BL/6 mice. V, vaccination; DP, depo-provera treatment; TB, tail bleeds; Spleens, harvested for ICS.

Table 1. Vaccine groups.

Group	Vaccine	Antigen Dose (μ g)	MPLA Dose	DDA Dose	LNP Dose
1	MPLA + DDA + LNP	-	5 μ g	250 μ g	100 μ g
2	Cm nMOMP + MPLA + DDA	10	5 μ g	250 μ g	-
3	Cm nMOMP + MPLA + LNP	10	5 μ g	-	100 μ g
4	Cm nMOMP + PmpG + MPLA + DDA	10/10	5 μ g	250 μ g	-
5	Cm nMOMP + PmpG + MPLA + LNP	10/10	5 μ g	-	100 μ g
6	Cm nMOMP + PmpG + PmpD p73 + PmpD p82 + MPLA + DDA	10/5/5/5	5 μ g	250 μ g	-
7	Cm nMOMP + PmpG + PmpD p73 + PmpD p82 + MPLA + LNP	10/5/5/5	5 μ g	-	100 μ g
8	Cm EBs	1×10^6 IFU	-	-	-

administered subcutaneously (2.5 mg/dose) on days 45 and 52 of the study prior to challenge. Mice were anesthetized in their home cage prior to challenge with a mixture of 85 mg/kg ketamine (Ketaset; Fort Dodge Animal Health, Fort Dodge, IA) and 5 mg/kg xylazine (AnaSed® Injection; Henry Schein Animal Health, Dublin, OH) by i.p. route. Mice were challenged intravaginally by direct instillation of 5000 IFU *C. muridarum* in 10 µl SPG on Day 55. The course of infection was monitored by enumerating *Chlamydiae* recovered from cervicovaginal swabs collected on days 62, 69, 76 using qPCR. The vaginal vault and ectocervix were swabbed using a microfiber swab (Fisher; Pittsburgh, PA). Swabs were placed into a 1.5 ml tube containing two sterile glass beads (5 mm diameter) and 300 µl of *Chlamydia* Isolation Medium (Trinity Biotech; Berkeley Heights, NJ) on ice. Bacteria were eluted from the swabs and separated from cells by vortexing for 60 seconds. Eluted bacteria were split into two aliquots and stored at -70°C until DNA extraction. Gross pathology was assessed on day 118. The experiment described hereafter was performed twice. The results were similar in both sets of experiments; for simplicity we will show the results of one study.

2.8. Primer, Probe and Real-Time Quantitative PCR

The qPCR assays were performed as described in Wooters *et al.* [20], with the following modifications. Briefly, DNA from genital swab samples (~100 µl) was extracted using the MagNA Pure 96 DNA and Viral NA small volume kit (Roche, Basel, Switzerland) on the MagNA pure machine (Roche, Basel, Switzerland) according to the manufacturer's instructions. The oligonucleotide primer set was designed for detection of all species of *Chlamydiae*. The sense primers, 16S DIR 5'-ATG CAT ATG ACC GCG GCA A-3', and 16S DIR 5'-ATG TAT ATG ACC GCG GCA GA-3' and anti-sense primer, 16S Rev 5'-TAA GGG CCA TGC TGA CTT GA-3', were designed to amplify a 508-bp fragment of the *Chlamydia* 16S ribosomal subunit gene, conserved across *Chlamydia* strains and serovars. Primers were obtained from Sigma-Aldrich (St. Louis, MO), and the probe, 16S Fam-5'-TTA ACC AGG AGG AAG GCG AG-3' Tamra, was also synthesized by Sigma-Aldrich (St. Louis, MO). The 50-µL reaction mixtures consisted of 1X QuantiTect Multiplex PCR master mix without ROX (Qiagen, Hilden, Germany), 100 nmol/L 16S probe, 200 nmol/L primer 16S DIR, 400 nmol/L primer 16S Rev, 30 nmol/L ROX reference dye, and 5 µL of sample DNA. Nontemplate controls consisting of the reaction master mix, primers, and probe, but no DNA, were included in each assay run. Reaction conditions were set as follows: 1 cycle at 95°C for 15 min, followed by 40 cycles at 94°C for 1 min and at 60°C for 1 min. Thermal cycling, fluorescent data collection, and data analysis were performed using the Stratagene Mx3005P system (Stratagene, San Diego, CA) according to the manufacturer's instructions. Data were plotted as Area Under the Curve (AUC) for individual mice and further analyzed by Wilcoxon Rank Sum Test (compared to MPLA/DDA/LNP).

2.9. Detection of Serum Antibody and Isotype Levels by ELISA

Serum was analyzed by an enzyme-linked immunosorbent assay (ELISA). Nunc™ C96 Maxisorp Immunoplates (Thermo Scientific, Waltham, MA) were coated with 50 µL of 1 µg/ml *C. muridarum* EBs in PBS at 4°C overnight. The plates were washed three times with PBS containing 0.05% Tween-20 (PBS-T) (Fisher Scientific, Hampton, NH). The wells were blocked with 5% Fetal Bovine Serum Albumin (BSA) (Thermo Scientific, Waltham, MA) in PBS-T at 200 µL/well for 1 hour at room temperature and washed three times with PBS-T. Serum was diluted in 5% FBS in PBS at a 1:500 dilution. Serially diluted sera were added to the plate, incubated for 2 hours at room temperature and were washed three times with PBS-T. HRP-conjugated secondary antibodies (Goat anti-mouse IgG, Fcγ fragment specific 1:6000; Goat anti-mouse IgG, Fcγ Subclass 1 specific 1:6000; or Goat anti-mouse IgG, Fcγ Subclass 2c specific 1:2000; Jackson ImmunoResearch Laboratories, Grove, PA) were diluted in 5% FBS in PBS. The diluted secondary antibodies were added at 100 µL/well, incubated for 1 hour at room temperature and were washed three times with PBS-T followed by three times with PBS. Room temperature BD Opt EIA™ TMB Substrate Reagent Set (BD Biosciences, Franklin Lakes, NJ) was mixed and filtered through a 0.22 µm cellulose acetate (CA) filter unit (Corning, Corning NY), and 100 µL was added to each well and incubated for 10 min at room temperature. The reaction was stopped with 100 µL/well of 2 M H₂SO₄ (Fisher Scientific, Hampton, NH). The optical density (OD) was read at 450 nm on a SpectraMax® M5 (Molecular Devices, San Jose, CA). The cutoff OD for each post-immunization serum was calculated as two times of the OD₄₅₀ of the corresponding pre-immunization serum. ELISA titers were determined by linearly interpolating between the sequential log dilutions that bracket the cutoff OD, where the dependent variable is the OD response and the independent variable is the log dilution. The resulting dilution is then back transformed to obtain the reported titer. The reported titer is the estimated dilution of serum that results in a response equivalent to the endpoint OD. Transformed data was analyzed by One-way ANOVA with Dunnett post test

2.10. T-Cell Intracellular Cytokine Staining

Ten days post final immunization, spleens from vaccinated animals were collected and processed to isolate splenocytes. One million splenocytes/well were incubated with 2 µg/ml of specific peptide pools for MOMP, PmpG or PmpD (15 mer overlapping by 11, custom order JPT Peptide Solutions, Germany) in the presence of Brefeldin A and anti-mouse CD28 and CD48b antibodies (BD Biosciences, Franklin Lakes, NJ). As a negative control, a sample for each was set up with a matched volume of DMSO and costimulatory antibodies, 5 hours post incubation at 37°C, splenocytes were incubated with mouse FC block (BD) surface stained with viability dye (Thermo Fisher, Waltham, MA) anti-mouse-CD3 (BD), CD4 (BD), CD8 (BD) followed by permeabilization and intracellular staining for anti-mouse IFNγ (BD), TNFα (BD), IL-2 (BD), and IL-17A (Biole-

gend), San Diego, CA). Fixed samples were then run on FACS LSRII flow cytometer (BD Biosciences, Franklin Lakes, NJ) and data were analyzed using FloJo software (Treestar Inc., Ashland, OR). The data analysis program Simplified Presentation of Incredibly Complex Evaluations (version 4.1.6; provided by M. Roederer, Vaccine Research Center, NIAID, NIH) was used to generate the graphical results in **Figure 2**. All peptide stimulated responses were reported after subtraction of the unstimulated controls. Responses were compared to the adjuvant only group (MPLA + DDA + LNP) in a two tailed paired t test.

3. Results

3.1. Recombinant and Native Protein Purification and Analytical Evaluation

PmpD (separated into the passenger domain p73 and translocator domains p82) and PmpG were cloned and expressed using pET vector systems. The recombinant proteins were expressed in the inclusion body fraction of IPTG-induced BL21DE3 cells. The inclusion body fractions were denatured, and recombinant proteins were purified and refolded (made soluble) using dialysis refolding techniques that provided high purity proteins for *in vitro* and *in vivo* use. All antigens tested had purities of >99% by 1D/LC-MS-MS analysis and were maintained in buffers (PBS with 0.1% Zwittergent, 3 - 14 or MES/NaCl with 0.1% Zwittergent, 3 - 14) that were suitable for both *in vitro* and *in vivo* studies. Native MOMP (nMOMP) was purified from large scale preps of *Chlamydia muridarum* infected HeLa cells. The nMOMP materials used in these studies were analyzed by amino acid analysis to determine concentration and then by 1D/LC-MS-MS analysis (purity > 95%), size exclusion chromatography with multi-angle light scattering detection to determine structure (predominantly trimer with some monomer), circular dichroism to determine form (~40% Beta-sheet structure), and SDS-PAGE analysis to confirm purity and structural characteristics. Extensive analytical evaluation of purified native MOMP similar to the protein used in these studies was described previously [21].

3.2. Immunization with *Chlamydia* Proteins Adjuvanted with LNP or DDA Induced Robust and Distinct Polyfunctional CD4 + T-Cell Response Profiles, and IL-17 Did Not Enhance Protection from Challenge

Due to the well-established connection between CD4 + T-cells and control of *Chlamydia*, we included potent T-cell adjuvants in our vaccine formulations [23] [23] [24] [25]. To explore the role of IL-17 in protection from *Chlamydia* challenge, we included formulations containing the cationic lipid, DDA, which was shown to be a potent promoter of IL-17 in previous vaccine studies [9]. Multiparameter flow cytometry was performed to evaluate antigen specific IFN- γ , TNF-a, IL-2 and IL-17 producing T-cells in splenocytes ten days after the final immunization (d40). Five mice per group were analyzed for ICS. A representative dot plot and gating strategy are provided in **Figure 3**.

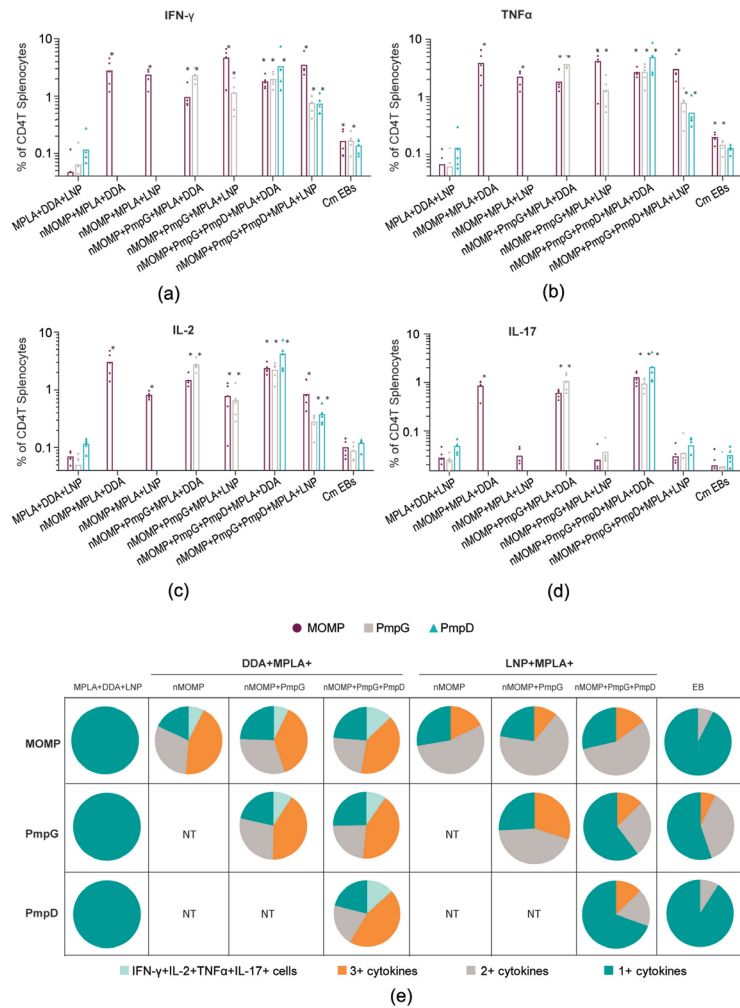


Figure 2. FACS. Antigen specific cytokine responses after immunization with Chlamydia proteins formulated with adjuvants. Splenocytes from the adjuvant control group, vaccine immunized groups and Cm EB vaccinated group were stimulated with 15 mer peptide pools corresponding to the vaccine antigens for each group (MOMP, PmpG, PmpD). Bar charts represent the percent of CD4 T cells producing IFN- γ (a), TNF- α (b), IL-2 (c) or IL-17 (d) as evaluated by multiparameter flow cytometry. Individual points within each open bar graph represent data from an individual mouse, and the height of the open bar depicts the mean response for the group. *depicts a significant difference ($p < 0.05$) in response as compared to the adjuvant only group (MPLA + DDA + LNP) in a two tailed paired t test. NT, not tested. Evaluation of the polyfunctional CD4 T cell response after vaccination. Boolean gates were created from the intracellular cytokine staining data to calculate the fraction of responding CD4 T cells producing each combination of cytokine production. Pie charts (e) display 4 + functions in light green (IFN γ + IL-2 + TNF α + IL17), 3 + functions in orange [(IFN γ - IL-2 + TNF α + IL17) or (IFN γ + IL-2 - TNF α + IL17+) or (IFN γ + IL-2 + TNF α - IL17+) or (IFN γ + IL-2 + TNF α -IL17-)], 2 + functions in gray [(IFN γ + IL-2 + TNF α -IL17-) or (IFN γ - IL-2 - TNF α + IL17+) or (IFN γ + IL-2 - TNF α + IL17-) or (IFN γ - IL-2 + TNF α + IL17-) or (IFN γ + IL-2 - TNF α -IL17+)] and monofunctional cells making any single cytokine in green. Vaccine antigens are listed at the top of the chart and grouped by vaccine adjuvant. Peptide pools to evaluate the responses are shown on the left of the graph. Vaccine test groups were evaluated for polyfunctionality for antigens in the respective vaccine regimen. NT = not tested for the described group.

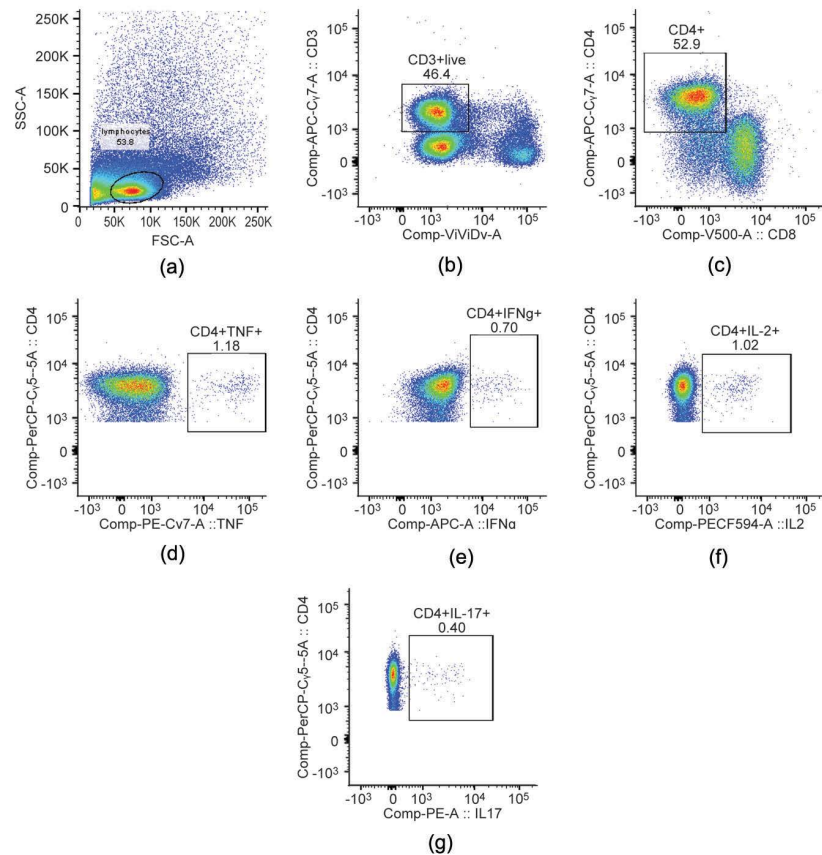


Figure 3. Representative flow cytometric staining example of ICS panel. Representative example and gating strategy for intracellular cytokine staining. An example of an antigen-specific response is shown. Lymphocytes were gated based on size and granularity, followed by a gate of CD3+ viable cells. Next, gates were placed on CD4T-cells. Next, CD4 T-cells were plotted for cytokine expression with a gate on the single positives for each (IFN γ , IL-2, TNF or IL-17). For each sample run, an unstimulated (DMSO matched to the peptide concentration) was used.

Robust MOMP specific CD4 + T-cells were observed in groups vaccinated with adjuvanted nMOMP (**Figures 2(a)-(e)**). Furthermore, MOMP responses of similar magnitude were detected from mice that were vaccinated with additional proteins (PmpG, PmpD) (**Figures 2(a)-(e)**), demonstrating a lack of immune interference.

Strong CD4 + T-cell responses specific for PmpD or PmpG were also detected in mice vaccinated with the respective adjuvanted proteins (**Figure 2**). Surprisingly, despite the increased protection afforded by the intraperitoneal *C. muridarum* elementary body immunization (**Figure 4**), mice in these groups demonstrated low levels of CD4 + T-cell responses in the spleen when stimulated with MOMP, PmpD and PmpG peptides. Compared to the adjuvant only control group, significant T-cell responses (IFN- γ and TNF- α) in EB exposed mice were only detected towards MOMP and PmpG (**Figure 2**). Additionally, these responses were much lower in magnitude as compared with the subcutaneous protein vaccinated groups.

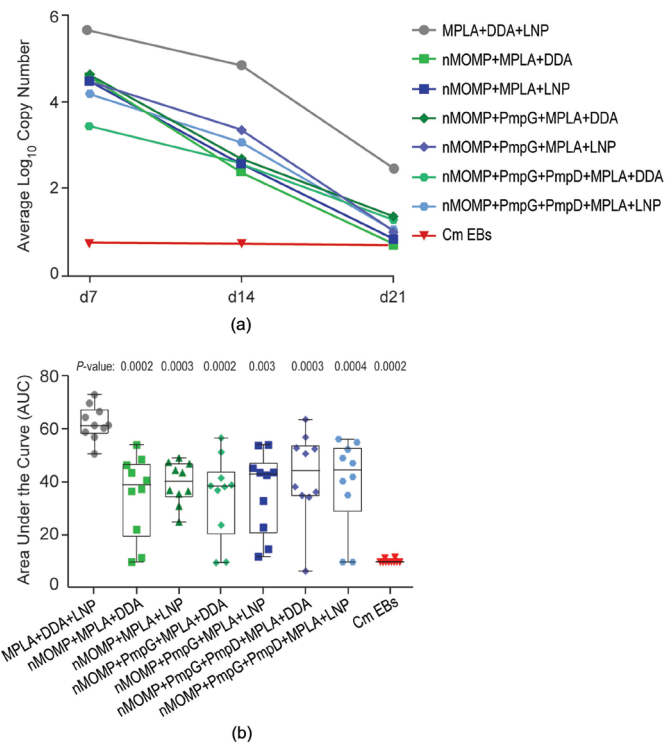


Figure 4. (a) (b) *Chlamydia muridarum* challenge in mice. *Chlamydia muridarum* challenge in mice. (a) Average copy numbers from real-time qPCR for each vaccine test group were plotted on Log₁₀ scale over days post challenge; (b) Area under the curve (AUC) values for individual mice were calculated and plotted and further analyzed by Wilcoxon Rank Sum Test to determine the p-values for each group (compared to MPLA/DDA/LNP group).

As expected, potent IL-17 responses were detected from mice in groups that were vaccinated with DDA containing formulations (Figure 2(d)), and such responses were not induced by the LNP formulations or *C. muridarum* EB exposure. Additionally, IL-2 cytokine production trended higher in the groups which received DDA (Figure 2(c)).

As polyfunctional T-cell responses have been shown to correlate with protection in many infectious disease models, we evaluated the percent of total responses in each group which produced all four cytokines (IFN- γ /IL-2/TNF- α /IL-17), any combination of the three, two or any one cytokine (Figure 2). Primarily due to significantly increased IL-17 and IL-2 production in the DDA adjuvanted vaccine groups (Figure 2(c) and Figure 2(d)), a higher percentage of polyfunctional T-cells were detected in the DDA adjuvanted vaccine groups as compared to the LNP or EB exposed groups (Figure 2(e)).

3.3. Vaccine Immunizations Result in High ELISA Titers to nMOMP, *C. muridarum* EBs, PmpG and PmpD

Animals were immunized with combinations of recombinant and native extracted proteins as per the scheme depicted in Table 1. An adjuvant control group with MPLA, DDA and LNP was used as a comparator against all test vac-

cine groups (10 animals per group). Each of the following combinations of antigens were formulated with MPLA + DDA or MPLA + LNP: nMOMP; nMOMP + PmpG; and nMOMP + PmpG + PmpD-p73 + PmpD-p82 (Table 1). A live Cm EB group was administered intraperitoneally as a positive control for protection against Chlamydia challenge [26] [27]. Sera collected prior to primary immunization and on day 42 were tested in ELISAs for antibodies to nMOMP, *C. muridarum* EBs, PmpG, PmpD-p73 and PmpD-p82. Anti-nMOMP IgG titers were high for all vaccine groups with the MPLA + LNP adjuvanted groups (3, 5, 7) inducing significantly higher ($P < 0.001$) IgG titers than MPLA + DDA adjuvanted groups (2, 4, 6) (Figure 5(a)). The IgG1/IgG2c ratios for MPLA + LNP groups compared to MPLA + DDA groups were not statistically different,

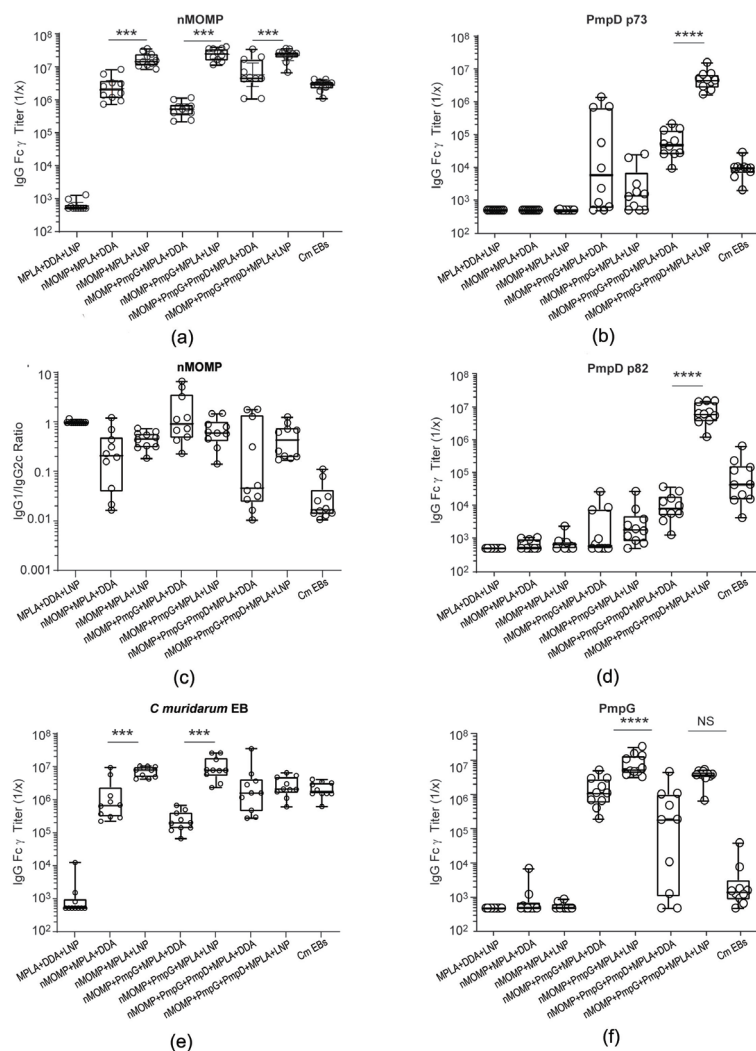


Figure 5. ELISA. IgG antibody titers to nMOMP, EB, PmpG, and PmpD as determined by ELISA. (a) Total IgG titers to nMOMP; (b) IgG1/IgG2c ratio of anti-nMOMP titers; (c) Total IgG titers to *C. muridarum* EBs; (d) Total IgG titers to PmpD p73; (e) Total IgG titers to PmpD p82; (f) Total IgG titers to PmpG. Error bars are geometric means with 95% confidence intervals. Transformed data analyzed by One-way ANOVA with Dunnett post test * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, **** $p < 0.0001$, NS not significant.

although the ratios indicate an overall balanced IgG1/IgG2c responses for most vaccinated groups with the exception of group 2 (nMOMP + MPLA + DDA), group 6 (containing all antigens: nMOMP, PmpG, PmpD-p73, PmpD-p82 + MPLA + DDA) and group 8 (live EB), which were lower, favoring IgG2c. However, comparisons of groups 1, 2, 6 or 8 were not statistically different from each other (data not shown). Groups with ratio's < 1 indicate more IgG2c thus suggesting a bias towards Th1/IL-17 cytokine responses (**Figure 5(b)**). All vaccine groups had high IgG titers to *C. muridarum* EBs, with MPLA + LNP adjuvanted groups (groups 3 and 5) having statistically higher ELISA titers than MPLA + DDA adjuvanted groups (groups 2 and 4) (**Figure 5(c)**). Those groups containing PmpD-p73 and PmpD-p82 had high PmpD IgG titers, with the MPLA + LNP adjuvanted group (group 7) having approximately 1 to 3 logs higher titers than the MPLA + DDA adjuvanted group (group 6) (**Figure 5(d)**, **Figure 5(e)**). Some cross reactivity to both PmpD-p73 and PmpD-p82 was observed for groups vaccinated with PmpG. Groups containing PmpG had high IgG titers to PmpG with the exception of group 6 (nMOMP + PmpG + PmpD p73 + PmpD p82 + MPLA + DDA) which had a wider range of titers against the Pmp antigens tested. Interestingly, PmpG antigens formulated with LNP, group 5 and 7, had higher titers than those formulated with DDA, groups 4 and 6, although only group 4 and 5 were significantly different ($P < 0.0001$) (**Figure 5(f)**).

3.4. Immunization with Native and Recombinantly Expressed Proteins Resulted in Early Clearance of *C. muridarum* Following Genital Tract Infection

Following immunization, animals were challenged with *C. muridarum* intravaginally (10 animals per group). Bacterial burden was assessed by swabbing the vaginal vault and ectocervix. Samples were then evaluated via qPCR as described previously [20]. Data were plotted as Area Under the Curve (AUC) for individual mice and further analyzed by Wilcoxon Rank Sum Test (compared to MPLA + DDA + LNP). All vaccine test groups with either adjuvant MPLA + DDA or MPLA + LNP had reduced bacterial burden and early clearance over time when compare to the adjuvant MPLA + DDA + LNP control group (**Figure 4**). The reduction in bacterial shedding from the vagina for all groups was statistically significant ($P < 0.001$), with Group 5 MOMP + PmpG + MPLA + LNP having a slightly lower statistical significance ($P = 0.003$). The EB positive control group also demonstrated greatly reduced *Chlamydia* shedding (**Figure 4**). Although the test vaccines appeared to decrease *Chlamydia* burden over the course of the infection, they failed to achieve the degree of protection provided by intraperitoneal administration of EBs. No statistical differences were observed between any of the vaccine groups (2 - 7). The EB positive control group was statistically lower than each of the vaccine test groups (2 - 7), p-values not shown.

4. Discussion

The development of an efficacious vaccine against *Chlamydia* is still an impor-

tant unmet medical need. Since the first vaccine trials in humans more than 50 years ago, there have been valiant efforts to produce a vaccine against *Chlamydia*, to prevent both trachoma and genital tract infections. The early human vaccine trials produced valuable information regarding the lack of efficacy of formalin inactivated whole *Chlamydia* vaccines and the possible immunopathology that resulted from their use. Additionally, over the years, animal models have elucidated the protective immune responses necessary to clear both primary and secondary infections. There is hope that these animal models will inform us about the human disease and the findings will translate to protection in humans. The murine primary protective immune response has been found to be MHC-II restricted CD4 + T-cells with MHC-I restricted CD8 + T-cells playing a less critical role in protection [22] [23] [24] [25]. Antibodies will also be important in vaccine development as the protective role for antibodies has been demonstrated in relation to reinfection following a primary *C. muridarum* infection in mice [28] [29] [30]. Cytokines of a Th1 profile such as IFN- γ and interleukin 12 (IL-12) are essential against *C. muridarum* infection in mice [31] [32]. In addition, IL-17 mediated immunity has been shown to play a role in the control of intracellular pathogens, including *Chlamydia* [9] [15]. However, there is also some evidence for a pathogenic role for IL-17 through enhanced recruitment of polymorphonuclear neutrophils and inflammatory monocytes in the UGT. The Th17-mediated inflammation has been associated tissue destruction and with intra-abdominal adhesions and increases in splenic weights in the mouse model [15] [16] [17].

In this study we compared subunit vaccines of native extracted MOMP either alone or in combination with other recombinantly expressed outer membrane MHC-II restricted proteins (PmpG, PmpD-p73 and PmpD-p82) to evaluate whether the addition of Pmp proteins would confer a greater reduction in bacterial shedding after challenge compared to nMOMP alone. In addition, we included various adjuvants to drive the cell mediated immune response toward Th1 and Th1/Th17 and to address the role of IL-17 in protection. The vaccines were adjuvanted with MPLA + DDA or MPLA + LNP and tested in C57Bl/6 mice. MPLA elicits a strong Th1 and balanced IgG1/IgG2 response when formulated with protein vaccines. LNPs when co-mixed with some sub-unit antigens result in strong B-cell responses, CD4 + and CD8 + T-cell responses [33]. The B-cell responses are typically Th2-like (based on IgG2a:IgG1 ratio). The antigen specific CD4 + and CD8 + T-cell responses boosted by LNP are typically polyfunctional: IFN- γ + TNF- α + IL-2+ [33]. DDA has been shown to increase Th1 responses yielding a mixed Th1:Th2 response and an increased IL-17 + response [34].

High systemic antibody titers were seen overall in this study. The MPLA + LNP adjuvanted groups had higher antibody titers when compared to MPLA + DDA adjuvanted group. Interestingly higher titers of antibodies in the MPLA + LNP groups did not translate to better clearance of *Chlamydia* following the intravaginal challenge. There can be several potential explanations for this ob-

servation, including higher amplitude of serum antibody titer may not reflect the antibody titers in the mucosal compartment thus not translating into improved protection from vaginal challenge. Furthermore, the functionality of the antibodies raised could be different for the two groups of adjuvanted formulations. Additionally, systemic or mucosal neutralizing antibody titers may be an important factor in protection from *Chlamydia*; however we did not evaluate them in these studies. We were able to establish different *C. trachomatis* in vitro neutralizing antibody assays according to Bryne *et al.*, but were unable to establish a reproducible *C. muridarum* neutralization assay [35].

In these studies, qPCR was used to analyze genital swabs for chlamydial shedding following a genital tract challenge. This technique is an acceptable way to evaluate bacterial shedding post challenge, but it does not determine viable *Chlamydia* nor does it quantitate IFUs. We observed a reduction in overall bacterial shedding in vaccine test groups that were statistically better than the adjuvant control group. An increased Th17 + response did not add to the protective immune responses nor did the addition of any of the Pmp family of antigens to a native MOMP vaccine elicit an increase in protection following intravaginal challenge. Our data also indicated that eliciting Th1 responses in the absence of Th17 responses were equally protective as MPLA + LNP formulations were comparable to MPLA + DDA formulations in terms of reducing the *Chlamydia* load after challenge. These data are consistent with publications that have shown that the protective immune response to *Chlamydia* infection appears to be correlated with a dominant Th1 and low Th17 T-cell response [26]. Mice in the DDA formulated groups did not have significantly lower bacterial shedding after challenge as compared to the mice in the LNP adjuvanted groups (Group 2 vs Group 3 p-value = 0.68, Group 4 vs Group 5 p-value = 0.38, Groups 6 vs Group 7 p-value = 0.31, **Figure 4**). This suggests that the ability of the DDA-formulated vaccines to elicit an IL-17 response did not confer greater protection from shedding than IFN- γ , IL-2 and TNF- α type Th1 response in this challenge model.

No significant differences were observed in reduction of pathology for any of the groups including the live EB immunized group in this study. Upper genital tract (UGT) pathology in our study was defined as dilation of uterine horns or fallopian tubes, or both. The adjuvant control, group 1, had 90% of the mice displaying UGT pathology and the vaccine groups (2 - 7) had 70% - 100% of mice with UGT pathology. The live EB immunized group had 60% UGT pathology and none of the groups were statistically different than the adjuvant control, group 1. Due to similar pathology observed across all adjuvanted groups and EB vaccinated group, the role of IL-17 in inducing pathology could not be determined. Consistent to our observation, it has been reported that EBs immunized intranasally were more resistant to genital tract pathology than EBs immunized intraperitoneally in mice upon subsequent intravaginal *Chlamydia* challenge. This observation could be postulated to better mucosal immunity upon intranasal immunization compared to intraperitoneal vaccinations. [26]. A good mucosal immune response may prevent *Chlamydia* ascension to the upper ge-

nital tract. Future studies could include, for academic purposes, intranasal immunization with live EBs to test whether this immunization route would be more resistant to genital tract pathology consistent with the literature.

Our nMOMP immunized groups conferred protection from challenge similar to previous publications [6] [7] [8]. For those groups combining nMOMP and either PmpD or PmpG or a combination of both PmpD and PmpG (PmpDG), we did not see an increased reduction of bacterial shedding compared to nMOMP alone after intravaginal challenge. Although this study was repeated and the results were similar for both experiments in our lab, the data are not in agreement to previous reports that showed the combination of Pmp E, F, G, H + MOMP reduced shedding over MOMP alone, PmpG alone, or the combination of Pmps [10]. However, it should be noted that there are several differences between the studies performed herein and those reported previously. Differences include the combination of Pmps, protein purification methods, study designs (antigen dose, adjuvants), assessment following challenge (sample collection, *Chlamydia* shedding assay), all of which may result in the observed differences in the result between the two studies. The Pmps in our study were selected based on recombinant protein expression and availability; a future study including additional recombinantly expressed Pmps such as E, F, and H could be informative. In addition to including more Pmps in a potential future study with stringent alignment for proteins used including purification protocols, adjuvants and shedding assessment methods could help understand the basis for discordant results.

5. Conclusion

In conclusion, we found that *Chlamydia* vaccines based on nMOMP provided modest protection against intravaginal challenge with *Chlamydia muridarum*. The efficacy of these vaccines could not be improved either by the incorporation of additional Pmp antigens, or by formulating the nMOMP antigen with adjuvants that either increased circulating anti-nMOMP IgG, or by eliciting a Th17 + response to nMOMP. An efficacious vaccine will require finding the optimal combination of antigens with several targets included and an adjuvant/immunization route combination that results in multifunctional CD4 + T cells and humoral responses elicited systemically and in the mucosal compartments.

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Availability of Data and Materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

All authors are employee of Merck & Co., Inc., West Point, PA, USA.

Authors' Contribution

MB is the primary author, and performed recombinant protein cloning and expression, and performed additional data analysis for ELISAs and qPCR evaluations. RK conducted the animal studies and performed ELISAs and data analysis of the ELISAs. KC ran the FAQ assays and performed the data analyses and authoring of the related sections for FAQ analysis. BL purified both recombinant proteins and native Momp proteins. JX, purified Chlamydia and ran ELISAs and performed data analysis for ELISAs. DN performed amino acid sequence analysis; ST ran qPCR testing and associated data analysis. AE, KV, and JS were pivotal in study design and conception. All authors have approved the manuscript.

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References

- [1] Beagley, K.W. and Timms, P. (2000) *Chlamydia trachomatis* Infection: Incidence, Health Costs and Prospects for Vaccine Development. *Journal of Reproductive Immunology*, **48**, 47-68. [https://doi.org/10.1016/S0165-0378\(00\)00069-3](https://doi.org/10.1016/S0165-0378(00)00069-3)
- [2] Brunham, R.C. and Rey-Ladino, J. (2005) Immunology of Chlamydia Infection: Implications for a *Chlamydia trachomatis* Vaccine. *Nature Reviews Immunology*, **5**, 149-161. <https://doi.org/10.1038/nri1551>
- [3] Morrison, R.P. and Caldwell, H.D. (2002) Immunity to Murine Chlamydial Genital Infection. *Infection and Immunity*, **70**, 2741-2751. <https://doi.org/10.1128/IAI.70.6.2741-2751.2002>
- [4] Gerbase, A.C., Rowley, J.T., Heymann, D.H.L., Berkley, S.F.B. and Piot, P. (1998) Global Prevalence and Incidence Estimates of Selected Curable STDs. *Sexually Transmitted Infections*, **74**, S12-S16.
- [5] CDC (2004) Chlamydia Screening among Sexually Active Young Female Enrollees of Health Plans—United States, 1999-2001. *Morbidity and Mortality Weekly Report*, **53**, 983-985.
- [6] Pal, S., Tatarenkova, O.V. and de la Maza, L.M. (2015) A Vaccine Formulated with the Major Outer Membrane Protein Can Protect C₃H/HeN, a Highly Susceptible Strain of Mice, from a *Chlamydia muridarum* Genital Challenge. *Immunology*, **146**, 432-443. <https://doi.org/10.1111/imm.12520>
- [7] Pal, S., Peterson, E.M., Rappuoli, R., Ratti, G. and de la Maza, L.M. (2006) Immunization with the *Chlamydia trachomatis* Major Outer Membrane Protein, Using Adjuvants Developed for Human Vaccines, Can Induce Partial Protection in a Mouse Model against a Genital Challenge. *Vaccine*, **24**, 766-775. <https://doi.org/10.1016/j.vaccine.2005.08.074>
- [8] Pal, S., Theodor, I., Peterson, E.M. and de la Maza, L.M. (1997) Immunization with an Acellular Vaccine Consisting of the Outer Membrane Complex of *Chlamydia trachomatis* Induces Protection against a Genital Challenge. *Infection and Immun-*

- ity*, **65**, 3361-3369. <https://doi.org/10.1128/IAI.65.8.3361-3369.1997>
- [9] Yu, H., Jiang, X., Shen, C., Karunakaran, K.P., Jiang, J., Rosin, N.L., *et al.* (2010) *Chlamydia muridarum* T-Cell Antigens Formulated with the Adjuvant DDA/TDB Induce Immunity against Infection That Correlates with a High Frequency of Gamma Interferon (IFN-Gamma)/Tumor Necrosis Factor Alpha and IFN-Gamma/Interleukin-17 Double-Positive CD4+ T Cells. *Infection and Immunity*, **78**, 2272-2282. <https://doi.org/10.1128/IAI.01374-09>
- [10] Yu, H., Karunakaran, K.P., Jiang, X. and Brunham, R.C. (2014) Evaluation of a Multisubunit Recombinant Polymorphic Membrane Protein and Major Outer Membrane Protein T Cell Vaccine against *Chlamydia muridarum* Genital Infection in Three Strains of Mice. *Vaccine*, **32**, 4672-4680. <https://doi.org/10.1016/j.vaccine.2014.06.002>
- [11] Yu, H., Karunakaran, K.P., Jiang, X. and Brunham, R.C. (2016) Subunit Vaccines for the Prevention of Mucosal Infection with *Chlamydia trachomatis*. *Expert Review of Vaccines*, **15**, 977-988. <https://doi.org/10.1586/14760584.2016.1161510>
- [12] Karunakaran, K.P., Yu, H., Jiang, X., Chan, Q., Moon, K.M., Foster, L.J., *et al.* (2015) Outer Membrane Proteins Preferentially Load MHC Class II Peptides: Implications for a *Chlamydia trachomatis* T Cell Vaccine. *Vaccine*, **33**, 2159-2166. <https://doi.org/10.1016/j.vaccine.2015.02.055>
- [13] Yu, H., Jiang, X., Shen, C., Karunakaran, K.P. and Brunham, R.C. (2009) Novel *Chlamydia muridarum* T Cell Antigens Induce Protective Immunity against Lung and Genital Tract Infection in Murine Models. *The Journal of Immunology*, **182**, 1602-1608. <https://doi.org/10.4049/jimmunol.182.3.1602>
- [14] Ralli-Jain, P., Tifrea, D., Cheng, C., Pal, S. and de la Maza, L.M. (2010) Enhancement of the Protective Efficacy of a *Chlamydia trachomatis* Recombinant Vaccine by Combining Systemic and Mucosal Routes for Immunization. *Vaccine*, **28**, 7659-7666. <https://doi.org/10.1016/j.vaccine.2010.09.040>
- [15] Vicetti Miguel, R.D., Quispe Calla, N.E., Pavelko, S.D. and Cherpes, T.L. (2016) Intravaginal *Chlamydia trachomatis* Challenge Infection Elicits TH1 and TH17 Immune Responses in Mice That Promote Pathogen Clearance and Genital Tract Damage. *PLoS ONE*, **11**, e0162445. <https://doi.org/10.1371/journal.pone.0162445>
- [16] Scurlock, A.M., Frazer, L.C., Andrews, C.W., O'Connell, C.M., Foote, I.P., Bailey, S.L., *et al.* (2011) Interleukin-17 Contributes to Generation of Th1 Immunity and Neutrophil Recruitment during *Chlamydia muridarum* Genital Tract Infection But Is Not Required for Macrophage Influx or Normal Resolution of Infection. *Infection and Immunity*, **79**, 1349-1362. <https://doi.org/10.1128/IAI.00984-10>
- [17] O'Meara, C.P., Harvie, M.C., Andrew, D.W., Timms, P., Lycke, N.Y. and Beagley, K.W. (2014) Immunity against a Chlamydia Infection and Disease May Be Determined by a Balance of IL-17 Signaling. *Immunology and Cell Biology*, **92**, 287-297. <https://doi.org/10.1038/icb.2013.92>
- [18] Lindstrom, T., Woodworth, J., Dietrich, J., Aagaard, C., Andersen, P. and Agger, E.M. (2012) Vaccine-Induced th17 Cells Are Maintained Long-Term Post-Vaccination as a Distinct and Phenotypically Stable Memory Subset. *Infection and Immunity*, **80**, 3533-3544. <https://doi.org/10.1128/IAI.00550-12>
- [19] Swanson, K.A., Taylor, L.D., Frank, S.D., Sturdevant, G.L., Fischer, E.R., Carlson, J.H., *et al.* (2009) *Chlamydia trachomatis* Polymorphic Membrane Protein D Is an Oligomeric Autotransporter with a Higher-Order Structure. *Infection and Immunity*, **77**, 508-516. <https://doi.org/10.1128/IAI.01173-08>
- [20] Wooters, M.A., Kaufhold, R.M., Field, J.A., Indrawati, L., Heinrichs, J.H. and Smith,

- J.G. (2009) A Real-Time Quantitative Polymerase Chain Reaction Assay for the Detection of Chlamydia in the Mouse Genital Tract Model. *Diagnostic Microbiology and Infectious Disease*, **63**, 140-147.
<https://doi.org/10.1016/j.diagmicrobio.2008.10.007>
- [21] Hepler, R.W., Nahas, D.D., Lucas, B., Kaufhold, R., Flynn, J.A., Galli, J.D., Swoyer, R., Wagner, J.M., Espeseth, A.S., Joyce, J.G., Cook, J.C. and Durr, E. (2018) Spectroscopic Analysis of Chlamydial Major Outer Membrane Protein in Support of Structure Elucidation. *Protein Science: A Publication of the Protein Society*, **27**, 1923-1941. <https://doi.org/10.1002/pro.3501>
- [22] Morrison, R., Feilzer, K. and Tumas, D.B. (1995) Gene Knockout Mice Establish a Primary Protective Role for Major Histocompatibility Complex Class II-Restricted Responses in *Chlamydia trachomatis* Genital Tract Infection. *Infection and Immunity*, **63**, 4661-4668. <https://doi.org/10.1128/IAI.63.12.4661-4668.1995>
- [23] Morrison, S.G. and Morrison, R.P. (2001) Resolution of Secondary *Chlamydia trachomatis* Genital Tract Infection in Immune Mice with Depletion of Both CD4+ and CD8+ T Cells. *Infection and Immunity*, **69**, 2643-2649.
<https://doi.org/10.1128/IAI.69.4.2643-2649.2001>
- [24] Morrison, S.G., Su, H., Caldwell, H.D. and Morrison, R.P. (2000) Immunity to Murine *Chlamydia trachomatis* Genital Tract Reinfection Involves B Cells and CD4(+) T Cells But Not CD8(+) T Cells. *Infection and Immunity*, **68**, 6979-6987.
<https://doi.org/10.1128/IAI.68.12.6979-6987.2000>
- [25] Rank, R.G., Soderberg, L.S. and Barron, A.L. (1985) Chronic Chlamydial Genital Infection in Congenitally Athymic Nude Mice. *Infection and Immunity*, **48**, 847-849. <https://doi.org/10.1128/IAI.48.3.847-849.1985>
- [26] Lu, C., Zeng, H., Li, Z., Lei, L., Yeh, I.T., Wu, Y., *et al.* (2012) Protective Immunity against Mouse Upper Genital Tract Pathology Correlates with High IFN γ But Low IL-17 T Cell and Anti-Secretion Protein Antibody Responses Induced by Replicating Chlamydial Organisms in the Airway. *Vaccine*, **30**, 475-485.
<https://doi.org/10.1016/j.vaccine.2011.10.059>
- [27] Yu, H., Karunakaran, K.P., Kelly, I., Shen, C., Jiang, X., Foster, L.J., *et al.* (2011) Immunization with Live and Dead *Chlamydia muridarum* Induces Different Levels of Protective Immunity in a Murine Genital Tract Model: Correlation with MHC Class II Peptide Presentation and Multifunctional Th1 Cells. *The Journal of Immunology*, **186**, 3615-3621. <https://doi.org/10.4049/jimmunol.1002952>
- [28] Farris, C.M., Morrison, S.G. and Morrison, R.P. (2010) CD4+ T Cells and Antibody Are Required for Optimal Major Outer Membrane Protein Vaccine-Induced Immunity to *Chlamydia muridarum* Genital Infection. *Infection and Immunity*, **78**, 4374-4383. <https://doi.org/10.1128/IAI.00622-10>
- [29] Igietseme, J.U. and Rank, R.G. (1991) Susceptibility to Reinfection after a Primary Chlamydial Genital Infection Is Associated with a Decrease of Antigen-Specific T Cells in the Genital Tract. *Infection and Immunity*, **59**, 1346-1351.
<https://doi.org/10.1128/IAI.59.4.1346-1351.1991>
- [30] Morrison, S.G. and Morrison, R.P. (2005) A Predominant Role for Antibody in Acquired Immunity to Chlamydial Genital Tract Reinfection. *The Journal of Immunology*, **175**, 7536-7542. <https://doi.org/10.4049/jimmunol.175.11.7536>
- [31] Perry, L.L., Feilzer, K. and Caldwell, H.D. (1997) Immunity to *Chlamydia trachomatis* Is Mediated by T Helper 1 Cells through IFN-Gamma-Dependent and -Independent Pathways. *The Journal of Immunology*, **158**, 3344-3352.
- [32] Roshick, C., Wood, H., Caldwell, H.D. and McClarty, G. (2006) Comparison of

- Gamma Interferon-Mediated Antichlamydial Defense Mechanisms in Human and Mouse Cells. *Infection and Immunity*, **74**, 225-238. <https://doi.org/10.1128/IAI.74.1.225-238.2006>
- [33] Swaminathan, G., Thoryk, E.A., Cox, K.S., Meschino, S., Dubey, S.A., Vora, K.A., *et al.* (2016) A Novel Lipid Nanoparticle Adjuvant Significantly Enhances B Cell and T Cell Responses to Sub-Unit Vaccine Antigens. *Vaccine*, **34**, 110-119. <https://doi.org/10.1016/j.vaccine.2015.10.132>
- [34] Klinguer-Hamour, C., Libon, C., Plotnicky-Gilquin, H., Bussat, M.C., Revy, L., Nguyen, T., *et al.* (2002) DDA Adjuvant Induces a Mixed Th1/Th2 Immune Response When Associated with BBG2Na, a Respiratory Syncytial Virus Potential Vaccine. *Vaccine*, **20**, 2743-2751. [https://doi.org/10.1016/S0264-410X\(02\)00193-7](https://doi.org/10.1016/S0264-410X(02)00193-7)
- [35] Byrne RSS, G.I., Ada, G., Caldwell, H.D., Su, H., Morrison, R.P., Van Der Pol, B., Bavoil, P., Bobo, L., Everson, S., Ho, Y., Hsia, R.C., Kennedy, K., Kuo, C.-C., Montgomery, P.C., Peterson, E., Swanson, A., Whitaker, C., Whittum Hudson, J., Yang, C.L., Zhang, Y.-X. and Zhong, G.M. (1993) Workshop on *In Vitro* Neutralization of *Chlamydia trachomatis*: Summary of Proceedings. *The Journal of Infectious Diseases*, **168**, 415-420. <https://doi.org/10.1093/infdis/168.2.415>

Abbreviations

IFU, inclusion forming unit; EB, elementary body; MOMP, major outer membrane protein; PmpG, polymorphic membrane protein G; PmpD, polymorphic membrane protein D; ICS, intracellular cytokine staining; IL-17, Interlukin-17; MPLA, Monophosphoryl lipid A; DDA, dimethyldioctadecylammonium bromide; UGT, upper genital tract.