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Lactobacillus-mediated priming of the respiratory mucosa protects against lethal pneumovirus infection*

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Abstract

The inflammatory response to respiratory virus infection can be complex and refractory to standard therapy. Lactobacilli, when targeted to the respiratory epithelium, are highly effective at suppressing virus-induced inflammation and protecting against lethal disease. Specifically, wild-type mice primed via intranasal inoculation with live or heat-inactivated *Lactobacillus plantarum* or *Lactobacillus reuteri* were completely protected against lethal infection with the virulent rodent pathogen, pneumonia virus of mice (PVM); significant protection (60% survival) persisted for at least thirteen weeks. Protection was not unique to *Lactobacillus* species, and was also observed in response to priming with non-pathogenic gram-positive *Listeria innocua*. Priming with live lactobacilli resulted in diminished granulocyte recruitment, diminished expression of multiple proinflammatory cytokines (CXCL10, CXCL1, CCL2, and TNF) and reduced virus recovery, although we have demonstrated clearly that absolute virus titer does not predict clinical outcome. *Lactobacillus* priming also resulted in prolonged survival and protection against the lethal sequelae of PVM infection in *MyD88* gene-deleted (*MyD88*$^{-/-}$) mice, suggesting that the protective mechanisms may be Toll-like receptor-independent. Most intriguing, virus recovery and cytokine expression patterns in *Lactobacillus*-primed *MyD88*$^{-/-}$ mice were indistinguishable from those observed in control-primed *MyD88*$^{-/-}$ counterparts, In summary, we have identified and characterized an effective *Lactobacillus*-mediated innate immune shield, which may ultimately serve as critical and long-term protection against infection in the absence of specific antiviral vaccines.

Keywords

Inflammation; Cytokines; Leukocytes; Pneumovirus; Pharmabiotic

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Introduction

Respiratory virus infections pose a major burden to society, both with regard to clinical illness and health care costs. Respiratory syncytial virus (RSV), a pneumovirus of the family *Paramyxoviridae*, is a chief cause of hospitalization for infants and young children and, likewise, results in significant morbidity and mortality in the elderly [1, 2]. In most infants and children, RSV bronchiolitis is self-limited, while in others, disease can progress to pneumonia and respiratory failure. Prematurity, multiple births, cardiovascular and pulmonary anomalies, and immunocompromised state are among the risk factors predisposing to severe RSV disease [3], although a recent prospective population-based surveillance study of acute RSV infection among children younger than 5 years of age indicated that most hospitalized children were previously healthy, with none of the documented risk factors [4]. The lack of a safe and effective vaccine for RSV and the expense and limited availability of prophylactic antibody therapy [5] represent serious hurdles in managing this significant public health problem.

In an effort to improve our understanding of the pathogenesis of severe pneumovirus infection *in vivo*, our laboratory has developed a model featuring the natural rodent pathogen, pneumonia virus of mice (PVM; [6, 7]). While no one animal model can replicate all the complexities of human disease, PVM has the advantage of undergoing robust replication and eliciting symptomatic disease in most inbred strains of mice [8]. With this model, we have documented molecular and cellular pathology, including granulocyte recruitment to the lung tissue and virus-induced production of proinflammatory cytokines; in doing so, we have highlighted parallels to the more severe forms of human RSV disease [9 – 11]. Using the PVM infection model, we have shown that morbidity and mortality depend largely on augmented inflammation, which can persist even when virus replication has been brought under control [12 – 14]. The importance of inflammation to the sequelae of severe respiratory virus infection has motivated our interest in immunomodulatory therapy [15] and, most recently, has led us to explore the immunotherapeutic potential of probiotic microbes and the expanding field of related microbial-derived biologics and biotherapies.

Probiotics are defined by the World Health Organization as “live microorganisms which, when administered in adequate amounts, confer a health benefit on the host” [16, 17]; recently, the term “pharmabiotic” has been introduced so as to include inactivated microorganisms, biologicals that influence live organisms, and therapeutically-active metabolites [18]. Among the most familiar of this target group are microorganisms of the genus *Lactobacillus*, which includes over 100 species of gram-positive bacteria that form lactic acid as a product of carbohydrate metabolism. Lactobacilli are best known as minor components of the commensal microflora of the mammalian gastrointestinal (GI) tract, and they have been popularized by the food industry for the purposes of acidification, flavor enhancement, and nutrition. Multiple human studies have demonstrated the immunotherapeutic properties of probiotic lactobacilli as nutritional supplements targeted to the GI tract, including prevention of acute diarrhea, alleviation of the symptoms of allergy, and therapy for inflammatory bowel disease [19, 20]. In mouse model studies, colony forming units (cfu) of *L. plantarum* were administered orally prior to influenza virus challenge; however all mice eventually succumbed to the lethal sequelae of infection [21]. Likewise, a recent review of randomized controlled trials in which humans with respiratory tract infections were treated orally with lactobacilli indicates little to no effect on disease incidence, as well as conflicting data on the duration of symptoms [22].

Given that lactobacilli clearly modulate inflammation at the GI epithelium, it is conceivable that that the oral route of administration is not optimal for regulating local responses to infection with respiratory pathogens. As such, we considered the possibility that targeting

live lactobacilli to the respiratory mucosa might result in a more effective immunomodulatory response, similar to the benefits observed when the intestinal mucosa is exposed directly to these organisms. To address this question, we primed the respiratory mucosae of mice with either *Lactobacillus plantarum*, an ecologically-flexible species first isolated from human saliva [23] or *Lactobacillus reuteri*, a common GI bacterium initially isolated from human feces [24], by direct intranasal inoculation with live microorganisms. We use the term "priming" to mean "providing a treatment that alters the capacity to respond to a second stimulus" (based on the definition in [25]), a phenomenon we observed upon administering lactobacilli directly to the respiratory epithelia of mice. Specifically, we found that mice primed with either of the two clinically-benign *Lactobacillus* species were completely protected from a subsequent lethal respiratory virus challenge. Here we explore the nature and characteristics of this response.

Materials and Methods

Mice

Wild-type BALB/c and C57BL/6 mice were purchased from Taconic Laboratories (Gaithersburg, MD). Homozygous *MyD88*$^{-/-}$ mice on a C57BL/6 genetic background were used with permission from Dr. Shizuo Akira [26]. All mouse experiments were performed in accordance with Animal Study Protocol LAD-8E, approved by the NIAID Animal Care and Use Committee.

Bacteria preparation and quantification

Lactobacillus plantarum NCIMB 8826 (ATCC BAA-793) and *Lactobacillus reuteri* F275 (ATCC 23272) were cultured overnight at 37°C in Difco Lactobacilli MRS Broth (BD Biosciences, Sparks, MD). *Listeria innocua* Seeliger (ATCC BAA-680) cultures were generated by overnight growth at 37°C in Sheep Brain Heart infusion medium (Thomas Scientific). Serial dilutions were plated and counted to correlate the number of colony-forming units per milliliter (cfu/mL) with the optical density at 600 nm (OD_{600}). Bacterial cultures were harvested by centrifugation (5 min, 1500 rpm), washed with phosphate-buffered saline (PBS), and suspended in PBS with 1% bovine serum albumin (BSA) just prior to inoculation. Inactivated bacteria were prepared by washing in PBS and heating to 95°C for 30 min prior washing in PBS and resuspension in PBS with 1% BSA; inactivation was confirmed by overnight culture in appropriate culture broths.

Virus preparation and quantification

Virions of PVM strain J3666 passaged *in vivo* as described [27] were quantitated by dual standard curve qRT-PCR targeting the PVM *SH* gene [28] to determine both virion copies per unit volume for inoculation (PVM_{SH}/μL) and virus recovery from infected mouse lung tissue (PVM_{SH}/GAPDH). Specifically, RNA was prepared from mouse lung tissue that had been immersed and stored in RNAlater (Ambion, Austin, TX) and subsequently isolated with RNAzol Bee (Tel-Test, Friendswood, TX). Isolated RNA was treated with DNase I to remove genomic DNA contaminants. Reverse transcription was performed using a first-strand cDNA synthesis kit (Roche; catalog no. 1,483,188) with random primers and a no reverse transcriptase control. The quantitative PCR reactions were runin triplicate, with the ABI 2x TaqMan reagent, primer-probe mixes, and cDNA or plasmid standard in a 25-μl final volume(Applied Biosystems). Thermal cycling parameters for the ABI7500 absolute quantitation program (Applied Biosystems) include50°C for 2 min (UNG incubation), 95°C for 10 min (AmpliTaqGold activation), and 40 amplification cycles alternating 95°C for 15 s and 60°C for 1 min. Primer-probe mixes include (1) GAPDH-Vic (Applied Biosystems catalog no. 4308313) to target GAPDH cDNA and (2) PVM_{SH}-Fam(custom design, primer 1, 5′-GCC GTC ATC AAC ACA GTG TGT-3′;primer 2, 5′-GCC TGA TGT GGC AGT

GCT T-3′; probe 6FAM-CGC TGATAA TGG CCT GCA GCA-TAMRA) to target the PVM SH gene to target the virus genome. GAPDH standard curve includes serial dilutions (10^7, 10^6, 10^5, 10^4, 10^3 molecules/reaction) of mouse GAPDH coding sequence in pCMV Sport 6 (from ATCC cat no. 10539385). PVM_{SH} standard curve includes serial dilutions(10^9, 10^8, 10^7, 10^6, 10^5 molecules per reaction) of the full-length PVM SH gene, GenBank (http://www.ncbi.nlm.nih.gov/nuccore) accession no. AY573815, in pBacPAK8. Experimental triplicate data pointsare interpolated to linear standard curves over the concentration ranges indicated. A sample calculation from data generated by this method is shown in Supplemental Figure 1.

Inoculations and sample collection

In our standard experimental protocol [Figure 1A], mice were anesthetized in 20% halothane in mineral oil and inoculated intranasally on days -14 and -7 with 10^9 cfu *L. plantarum*, *L. reuteri*, or control (PBS + 1% BSA) in a 50 μL volume. On day 0, *Lactobacillus*- or control-primed mice were inoculated with 50 μL PVM diluted 1:3000, to 2000 virion copies PVM_{SH} per μL in Iscove's Modified Dulbecco's medium (IMDM). At selected time points, mice were sacrificed by cervical dislocation under anesthesia, and mice were subjected to trans-oral bronchoalveolar lavage (BAL) with PBS + 1% BSA, yielding 800 μL per mouse. Whole lung tissue was stored in RNA*later* (Ambion, Austin, TX) for RNA isolation, detailed elsewhere [28] or blade-homogenized in ice-cold IMDM, followed by centrifugation at 4°C for preparation of clarified tissue homogenates. Clarified supernatants were stored in aliquots at −80°C until use.

Histopathology

On day 7 of our treatment protocol, lungs of sacrificed mice were inflated trans-tracheally using 250 μL 10% phosphate-buffered formalin. The lungs and heart were removed and fixed overnight in 10% phosphate-buffered formalin at 4°C. Samples were paraffin-embedded, sectioned, and stained with hematoxylin and eosin (Histoserv, Inc., Germantown, MD).

Single cell suspensions

Single cell suspensions were generated from mouse lung tissue as described [29]. Lungs were perfused with 5 – 10 mL PBS + 10 mM EDTA and placed in digestion medium, consisting of Roswell Park Memorial Institute (RPMI)-1640 medium (Invitrogen) supplemented with 5% fetal bovine serum (BioWhittaker, Walkersville, MD), 20 μg/mL grade II DNase I (Roche Diagnostics, Mannheim, Germany), and 40 μg/mL Collagenase D (Roche). The tissue was cut into ~3 mm^3 pieces and incubated in digestion medium (37°C, 90 min, with rocking). Upon adding cold EDTA (10 mM) to the cell suspension, the cells were passed through a 40-μm Nylon cell strainer (BD Biosciences, Durham, NC) and washed with PBS supplemented with 0.3% BSA, 5 mM EDTA, and 20 μg/mL DNase I. Cells were centrifuged (5 min, 1500 rpm), red blood cells eliminated with 1 mL ACK Lysing Buffer (BioWhittaker) for 2 minutes as needed, and remaining cells washed again. All cell pellets from a given condition were pooled and resuspended in HBSS at a density of 10^6 cells/mL. Cells were treated as described below, fixed with PBS + 4% paraformaldehyde, washed, and stored at −80°C in PBS + 10% DMSO.

Flow cytometry

Prior to fixation, lung cells (~10^6 cells per condition) were blocked with anti-mouse CD16/CD32 mAb (BD Biosciences) and, as appropriate, stained with LIVE/DEAD violet-fluorescent reactive dye (Invitrogen, Eugene, OR) and/or DX-5 PE (BD Pharmingen; applied prior to fixation) in PBS + 1% BSA. Antibody-fluorochrome conjugates included

B220 Alexa-Fluor 488, CD3 PE-Cy5, CD4 PerCP-Cy5.5, CD8 APC-Cy7, and GR1 APC (BD Pharmingen). Cells were stained for 30 minutes at 4°C, washed with PBS + 1% BSA, and analyzed using a LSR II flow cytometer in conjunction with FACSDiva software (BD Biosciences), with a minimum of 100,000 events collected per sample.

Cytokine expression

RNA from mouse lung tissue was isolated, pooled (12 μg total RNA per condition), and purified using the RT^2 qPCR-grade RNA Isolation Kit (SA Biosciences, Frederick, MD). First-strand cDNA was generated using the RT^2 First-strand Kit (SA Biosciences) and, in conjunction with the RT^2 SYBR Green/ROX qPCR Master Mix (SA Biosciences), analyzed for differential gene expression using the RT^2 Profiler Mouse Inflammatory Cytokines and Receptors PCR Array (SA Biosciences). ELISA analysis was performed to quantify immunoreactive proteins using Quantikine™ kits from R&D Systems (Minneapolis, MN) as per manufacturer's instructions. Datapoints generated using lung tissue homogenates were normalized to total protein per sample, which was determined via BCA protein assay (Pierce, Rockford, IL) with BSA standards.

Microarray data

Our microarray dataset (M430-2 chip) documents the normalized expression profiles of 39,000 transcripts expressed in mouse lung response to PVM infection over time [30]. Profiles of specific chemokine transcripts were determined via algorithms within Genespring GX7.3 (Agilent Technologies).

Detection of granulocytes

Granulocytes were evaluated in BAL fluid at days indicated using modified Giemsa staining (Diff-Quik, Fisher Scientific, Pittsburgh, PA). To prepare cells for staining, BAL fluids were subjected to centrifugation, and the cell pellets were resuspended in PBS + 1% BSA. 10^5 cells were centrifuged onto slides using a Shandon Cytospin apparatus (Thermo Electron, Pittsburgh, PA). Following staining and mounting of cells, ten high-power fields were visually inspected by light microscopy.

Seroconversion

Mouse sera were isolated from tail bleeds via standard procedures and assessed for seroconversion (immunoreactivity to PVM antigens) using the SMART-M12 PVM Kit (Biotech Trading Partners, Encinitas, CA), per manufacturer's guidelines.

Lactobacillus clearance

Mice were inoculated with 10^9 cfu *L. plantarum* or *L. reuteri* and sacrificed at 1, 2, 3 and 7 days thereafter; lungs were blade-homogenized in 1 mL sterile PBS + 1% BSA. Homogenates (100 μL) were plated at 1:1, 1:20, or 1:100 on MRS agar and incubated overnight at 37°C. Homogenates from PBS + BSA-treated mice were included as controls.

Statistical analysis

Data were evaluated using Welch's *t* test, Mann-Whitney *U* test, ANOVA with Bonferroni's multiple comparison test, or the log-rank test for survival curves, as appropriate. All statistical tests were included in the GraphPad Prism 5 software package (La Jolla, CA). Significant outliers were identified using the Grubbs test. All bar graphs indicate the mean ± the standard error of the mean (SEM).

Results

Priming of the respiratory mucosa with lactobacilli results in protection from lethal pneumovirus infection

The first question motivating our study was whether direct stimulation or priming of the respiratory mucosa with live lactobacilli would alter the outcome of a lethal pneumovirus infection. To explore this question, we devised a standard protocol whereby mice were primed with two intranasal inocula (on days -14 and -7, respectively), each containing 10^9 colony-forming units (cfu) of live *L. plantarum* or *L. reuteri*; these inocula were followed by intranasal challenge with pneumonia virus of mice (PVM) on day 0 [Fig. 1A]. We found that BALB/c mice primed in this fashion were fully protected from an otherwise lethal respiratory virus infection [Fig. 1B]. BALB/c mice responded to *Lactobacillus* priming with transient granulocyte recruitment [Fig. 1C]. *Lactobacillus* priming alone resulted in no acute mortality, and we observed complete clearance of live lactobacilli from the lung tissue within 7 days after inoculation (data not shown). Direct *Lactobacillus* priming of the respiratory mucosa resulted in protection from lethal sequelae of virus infection even when challenge was delayed from day 0 until day 7 or day 21 [Table 1] and we observed prolonged survival and significant long-term protection even when virus challenge was delayed until 91 days (13 weeks) after initial priming [Fig. 1D]. Priming with heat-inactivated *L. plantarum* (10^9 cfu equivalents) also generated protection against lethal virus challenge [Fig. 2A], as did priming with live or heat-inactivated gram-positive *Listeria innocua* [*L. innocua*; Fig. 2B], indicating that these findings are not unique to *Lactobacillus* species. Of note, neither live nor heat-inactivated *L. plantarum* were effective when administered therapeutically, three days after virus inoculation, rather than as a priming agent [Fig. 2C].

Virus recovery from lungs of *Lactobacillus*- and PBS-primed mice

Virus recovery from whole lung tissue was determined on days 3, 5 and 7 after PVM challenge [Fig. 3A]. Virus replication was detected in *Lactobacillus*-primed as well as PBS-primed mice, and seroconversion to PVM antigens was detected in all mice surviving infection (data not shown). Significantly fewer virion copies were detected in lungs of *L. plantarum*-primed compared to PBS-primed mice on all days evaluated (4 – 30-fold). Virus recovery from the lungs of *L. reuteri*-primed mice was also somewhat diminished compared to PBS-primed mice on day 3 (5-fold) and on day 7 (4-fold), but there was no significant difference between virus recoveries at peak. Despite this latter finding, all *L. reuteri*-primed mice survived virus infection (100%), whereas 95% of the PBS-primed mice did not [Fig. 1B]. These results suggest that *Lactobacillus*-mediated alteration of virus kinetics (replication and clearance) may not provide a sufficient explanation for differential survival. In order to evaluate the relationship between virus recovery and survival directly, ten *L. plantarum* (LP) and ten PBS (PBS + 1% BSA) primed mice were inoculated on day 0 with PVM (standard protocol, Fig. 1A), with the virus inoculum received by the control (PBS-primed) mice reduced to 600/μL, so that peak virus recoveries (day 5) would be comparable. Five mice were selected randomly from each group for determination of virus recovery. As anticipated, differences in peak virus recoveries were insignificant [Fig. 3B], yet none of the remaining PBS-primed, virus-infected mice survived beyond day 9, while all of the remaining LP-primed, virus-infected mice survived long-term [Fig. 3C, $^{**}p < 0.01$]. From these findings we conclude that, while *Lactobacillus* priming modulates virus replication and clearance, virus recovery alone cannot predict disease outcome or long-term survival.

Lung histopathology and differential leukocyte recruitment

In alignment with our previous studies [12, 13], lungs of control-primed, PVM-infected mice revealed a profound alveolitis, with widespread, diffuse granulocyte recruitment and

early-onset edema [Figs. 4A–4C]. In contrast, the lungs of *L. plantarum*-primed, PVM-infected mice exhibited minimal inflammation peripherally and feature compact, peribronchiolar and perivascular cuff-like infiltrates, consistent with descriptions of induced bronchus-associated lymphoid tissue (iBALT; [Figs. 4D – 4F] [31, 32]).

Consistent with these histopathologic findings, priming with *L. plantarum* prior to PVM infection resulted in a 5-fold reduction in the fraction of $GR1^+$ granulocytes [Fig. 5A and 5B] and a concomitant 2-fold increase in the fraction of lymphocytes in whole-lung single-cell suspensions compared to PBS-primed, PVM-infected controls [Fig. 5B]. Additional analysis of the lymphocyte populations revealed that *Lactobacillus* priming prior to PVM infection had no impact on the relative proportions of $CD4^+$ T cells ($CD3^+CD4^+CD8^-$), $CD8^+$ T cells ($CD3^+CD4^-CD8^+$), or B cells ($B220^+$), while the fraction of NK cells ($CD3^-DX5^+$) was diminished [Fig. 5C].

Suppression of virus-induced proinflammatory cytokines

Morbidity and mortality in response to severe respiratory virus infection can result in large part from uncontrolled amplification of proinflammatory signaling networks [33]. We observed that *Lactobacillus* priming of the respiratory mucosa resulted in suppression of multiple cytokines associated with the inflammatory pathology of respiratory virus infection. Specifically, priming with lactobacilli resulted in marked suppression of interferon-inducible protein (CXCL10/IP-10), monocyte-chemotactic protein 1 (CCL2/MCP-1), neutrophil-activating protein-3 (CXCL1/NAP-3), macrophage inflammatory protein-1γ (CCL9/MIP-1γ), tumor necrosis factor (TNF) and eotaxin-2 (CCL24) [Fig. 6A]. CCR1 is a prominent CC chemokine receptor detected on granulocytes [34]; differential detection of this transcript is consistent with the flow cytometric results shown in Figs. 4A and 4B. Of note, *Lactobacillus*-mediated suppression of CXCL10 and CCL2 was evident as early as day 4 after virus inoculation [Suppl. Fig. 2]. Cytokine mediators determined as not differentially expressed in response to *Lactobacillus*-priming included CCL3, CCL5, CXCL12, and TGF-β1. CXCL10, CCL2, and CXCL1 are expressed prominently in mouse lung tissue in response to PVM infection. These proinflammatory mediators are among those with transcriptional profiles that parallel respiratory dysfunction as detected in our PVM gene expression microarray database [30], which documents the full spectrum of transcriptional responses to the PVM pathogen in otherwise unmanipulated wild-type mice [Suppl. Fig. 3]. Immunoreactive CXCL10, CCL2, CXCL1, and TNF were detected in BAL fluid of PBS-primed, PVM-infected mice; expression was suppressed in mice primed with lactobacilli, most notably expression of CCL2 (~20-fold suppression) [Fig. 6B]. Interestingly, we detected expression of both interferon-β (IFN-β) and interleukin-10 (IL-10) in response to PVM infection, but neither of these cytokines, implicated in *Lactobacillus*-mediated immunomodulation in a variety of other settings [35 – 38], were detected as differentially expressed in response to *Lactobacillus*-priming in BALB/c mice [Fig. 6C].

MyD88-dependent signaling, virus recovery and differential survival

Previous studies published by several groups have identified *Lactobacillus*-mediated immunomodulatory mechanisms that are dependent on Toll-like receptors (TLRs), primarily TLR2 and TLR4 [39]. As an initial exploration of the TLR dependence of *Lactobacillus*-mediated protection against virus infection, we carried out our inoculation protocol with mice devoid of MyD88 ($MyD88^{-/-}$), the (near) universal TLR adapter protein. These mice were available to us on the C57BL/6 background. Mice of this background are less susceptible to the lethal sequelae of PVM infection than are BALB/c mice at the same virus inoculum [40]. *Lactobacillus*-mediated priming was effective at preventing lethal sequelae of PVM infection in the C57BL/6 background [Fig. 7A]. Although some mortality was observed among the *L. plantarum*-primed $MyD88^{-/-}$ mice at this virus inoculum, priming of

the respiratory mucosa resulted in prolonged survival and significant long-term protection against the lethal sequelae of virus infection for a substantial fraction of mice [Fig. 7B]. Analysis of the differential survival [Suppl. Fig. 4] documents that TLR-MyD88 signaling did not contribute substantially to *Lactobacillus*-mediated protection. Similar to what was observed in experiments performed with control- and *L. plantarum*-primed wild-type BALB/c mice [Fig. 3A], *Lactobacillus* priming of C57BL/6 mice resulted in diminished virus recovery from lung tissue [~5-fold; Fig. 7C]. Virus recovery from lungs of control-primed *MyD88*$^{-/-}$ mice was not significantly different from that measured in the control-primed wild-type C57BL/6 mice. Likewise, virus recovery from lungs of *L. plantarum*-primed *MyD88*$^{-/-}$ mice was indistinguishable from that of the control-primed *MyD88*$^{-/-}$ mice, despite clear evidence of differential survival within this genotype [Fig. 7B]. These results are consistent with those shown in Fig. 3, and stand in support of our earlier conclusion, that although *Lactobacillus*-priming has a significant impact on virus recovery, virus titer in lung tissue does not serve as a predictor of disease outcome or long-term survival.

MyD88-dependent signaling, virus infection and proinflammatory cytokines

Initial identification of specific proinflammatory mediators that were differentially expressed in *Lactobacillus*-primed, PVM-infected vs. control-primed, PVM-infected lung tissue from BALB/c mice was determined by PCR array of 84 potential transcripts and confirmed by ELISA [Fig 6, see Methods]. As shown in Fig. 8, differential cytokine expression in *L. plantarum*-primed vs. control-primed, PVM-infected wild-type C57BL/6 mice is comparable to what was determined in wild-type BALB/c mice. Specifically, we observed profound suppression of CCL2 and CXCL10 [Fig. 8A and 8B], and moderate suppression of CXCL1 and TNF [Fig. 8C and 8D]. Of note, significant suppression of interleukin-10 was observed in *L. plantarum*-primed, PVM-infected C57BL/6 mice [Fig. 8E]; this was not observed in BALB/c mice. All of these cytokines were detected in lung tissue of PVM-infected *MyD88*$^{-/-}$ mice, albeit at significantly reduced concentrations as compared to PVM-infected C57BL/6 wild-type mice (save for TNF, which is detected at levels that are not statistically different from control-primed, PVM-infected wild-type C57BL/6 mice). Interestingly, *Lactobacillus*-mediated cytokine suppression was not detected in *MyD88*$^{-/-}$ mice. Thus, differential cytokine expression is not a crucial feature of *Lactobacillus*-mediated protection in the absence of TLR-MyD88 receptor signaling.

Discussion

In this study we demonstrate that priming of the respiratory mucosa with non-pathogenic gram-positive microorganisms results in full protection from the otherwise lethal sequelae of severe pneumovirus infection. Protection is observed in response to both live and heat-killed *Lactobacillus* strains (*L. plantarum* and *L. reuteri*) and live and heat-killed gram-positive *Listeria innocua*, which, although not pathogenic, had not been considered previously as a potential probiotic or pharmabiotic microorganism. Administration of live lactobacilli directly to the respiratory mucosa resulted in diminished virus recovery at multiple time points and prominent suppression of virus-induced proinflammatory mediators.

Although virus recovery is diminished in response to *Lactobacillus* priming, similar to results obtained by several other groups in experiments with influenza virus [41 – 43], here we build on these findings, as we examine the unique responses to priming and the specific relationship to virus recovery and cytokine production. First, we have determined clearly that virus recovery does not correlate with disease outcome. Specifically, virus inocula were altered so that peak virus recoveries in *Lactobacillus*-primed and control-primed wild-type mice were comparable to one another. Nevertheless, *Lactobacillus*-primed mice proceeded to survive long-term, and the control-primed mice succumbed to the lethal sequelae of virus infection. These findings are consistent with our earlier studies on the pathogenesis of PVM

infection in wild-type mice, in which we determined that virus recovery alone cannot predict outcome of disease, and that the virus-induced inflammatory response can lead to lethal sequelae even after initial replication is blunted with effective antiviral therapy [12, 13]. Given our current understanding of the immunomodulatory capacity of lactobacilli at the GI mucosa, including modulation of cytokine production by target epithelial cells [16 – 17, 19, 44], our primary hypothesis was that the major protective role of lactobacilli at the respiratory mucosa was directly related to their ability to suppress local virus-induced inflammatory responses.

Upon further analysis, we found the relationship between virus-induced inflammation and *Lactobacillus*-mediated protection to be more complex than previously anticipated. We observed that mice devoid of the gene encoding the MyD88-TLR signaling adaptor were also protected from the lethal sequelae of PVM infection after priming with *L. plantarum*. Clearly, this does not rule out potential roles played by TLR-mediated signaling pathways that circumvent *MyD88* or other pattern-recognition receptors that may play a role in sensing *Lactobacillus* species [45, 46]; TLR-desensitization has been observed as a mechanism that explains reduced inflammatory responses observed after recuperation from influenza virus [47]. The data on TLR signaling in response to lactobacilli is complex and, to date, no consensus findings or aligning principles have emerged. For example, Hisbergues and colleagues [48] reported that mouse bone marrow-derived dendritic cells produce both IL-10 and IL-12 in response to *L. plantarum* via TLR-2/MyD88-dependent and TLR4/MyD88-independent pathways. At the same time, Ichikawa and colleagues [49] reported that cells from mouse spleen and mesenteric lymph node produce IL-12 in response to *L. paracasei* via pathways that are *MyD88*-dependent, but completely independent of TLR2, TLR4 or TLR9. In contrast, Chung and colleagues [50] found that *L. casei*-mediated protection in the mouse model of dextran-sulfate sodium-induced colitis was primarily dependent on signaling via TLR4. At this point in time, it is not clear whether responses are defined by an individual *Lactobacillus* species or strain, unique to a given organ or tissue, or whether they are specified by mouse genotype or functional overlap of specific signaling pathways.

Of note, this is the also the first documented evaluation of PVM infection *in vivo* in *MyD88* gene-deleted mice. Virus recovery from $MyD88^{-/-}$ mouse lung tissue was similar to that reported by Bhoj and colleagues [51] in their study of RSV clearance. However, in contrast to these findings, we observed accelerated replication of PVM in $MyD88^{-/-}$ eosinophilic granulocytes from bone marrow cultures [52]. The role of individual TLRs in mediating responses to pneumovirus infection remains incompletely explored [reviewed in 53]; TLR 2/6, TLR4, and TLR7 have all been implicated in augmenting immune responses in the RSV challenge mouse model, while closely-related mouse pathogens Sendai virus (parainfluenza virus 1) and PVM do not engage TLR4 [54, 55].

Similar to findings described for wild-type mice, *Lactobacillus*-priming promoted survival in PVM-infected $MyD88^{-/-}$ mice, but in contrast, promoted no differential expression of proinflammatory mediators, CCL2, CXCL1, CXCL10, TNF. These cytokines are all mediators that are prominently suppressed in association with *Lactobacillus*-mediated protection in wild-type mice. Although there are no unique roles attributed to any of these mediators in the pathogenesis of pneumovirus disease, collectively they have been implicated in promoting disease severity in a variety of settings. For example, the chemokine CCL2 has been detected in BAL fluid from RSV-infected infants [9, 56], in RSV-challenged mice [57], and levels of this mediator correlate with respiratory dysfunction in the PVM infection model [30]. Similarly, although CXCL10 has not received as much attention vis-à-vis the pathogenesis of pneumovirus-induced bronchiolitis [58], McNamara and colleagues [9] examined a series of BAL samples from infants intubated secondary to

RSV bronchiolitis and detected CXCL10 as one of the two predominant chemokines. TNF has likewise been associated with severe RSV disease in several human studies [59, 60]. Overall, our findings introduce an interesting and important conundrum, as it is clear that *Lactobacillus*-mediated protection is associated with diminished levels of multiple proinflammatory cytokines, but, given the fact that protection can be elicited in *MyD88*$^{-/-}$ mice without evidence for this suppression, it is clear that this may be only one aspect of the overall protective mechanism. Among the possibilities, *Lactobacillus* priming may elicit multiple parallel, potentially degenerate responses that may compensate for one another (e.g. *MyD88*-independent pathways eliciting protection in equal force, duplicating the efforts of the derailed *MyD88*-dependent pathways). Given the variety and complexity of potential immunostimulants presented by unfractionated gram-positive organisms (i.e. peptidoglycan, lipoteichoic acid, membrane proteins), this is a reasonable possibility that will require careful mechanistic dissection.

In summary, we have observed that priming of the respiratory mucosa with clinically-benign gram-positive *Lactobacillus* species results in markedly diminished inflammatory responses upon challenge with a pneumovirus pathogen, and *Lactobacillus*-primed hosts are fully protected from the otherwise lethal sequelae of a severe respiratory virus infection. We demonstrate that virus recovery from lung tissue is not a predictor of disease outcome. Our goal is to characterize the protective responses at the molecular level and at the same time to determine a means by which lactobacilli might be used as a broad-spectrum respiratory mucosal immunomodulatory agent. These lactobacilli, or components thereof, may serve as an effective innate immune shield to provide critical protection against pneumovirus, and perhaps other severe respiratory virus infections, prior to the development of safe, specific, and reliable vaccines.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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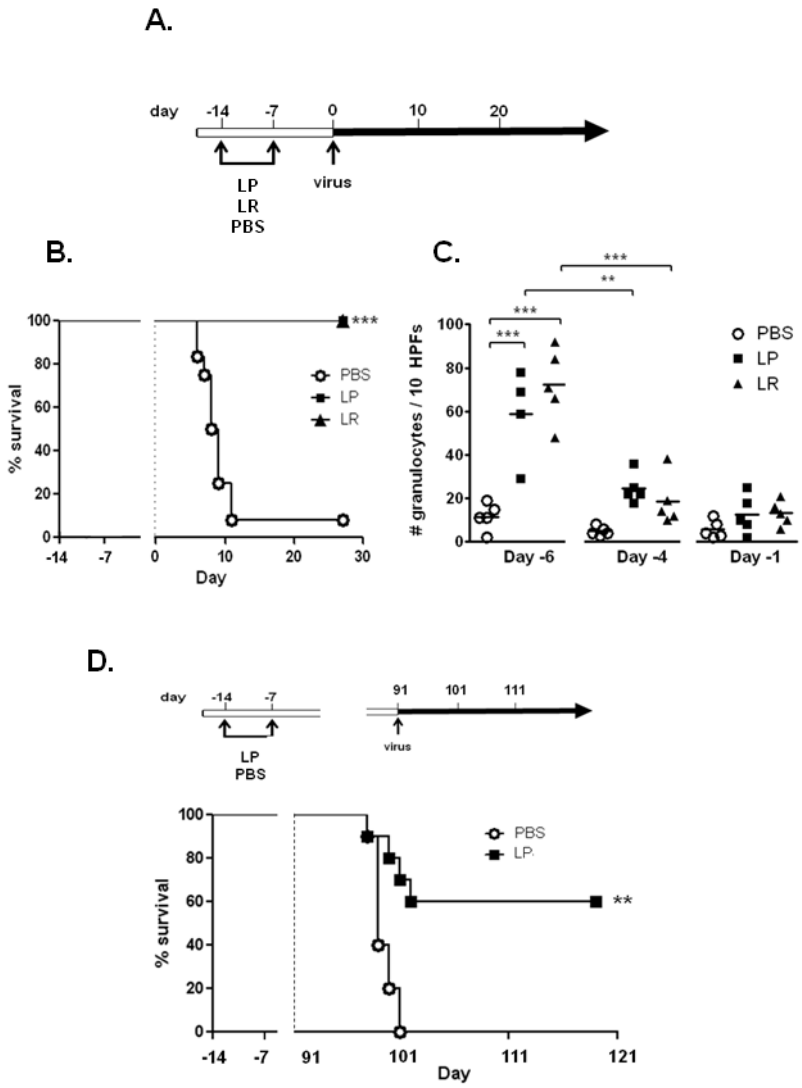

Figure 1. Priming of the respiratory mucosa with live lactobacilli results in protection from an otherwise lethal virus infection

A. Standard experimental protocol. On days -14 and -7, BALB/c mice were inoculated intranasally with 10^9 cfu *L. plantarum* (LP), 10^9 cfu *L. reuteri* (LR), or PBS + 1% BSA vehicle control (PBS). On day 0, all mice were inoculated with pneumonia virus of mice (PVM; 2000 virion copies/μL). **B.** Survival of mice inoculated as indicated with LP, LR or PBS prior to virus infection, n = 10 mice per group, representative of at least two independent experiments; ***$p < 0.001$ **C.** Granulocytes detected in bronchoalveolar lavage (BAL) fluid at time points indicated (day -6, day -4, day -1 as per Fig. 1A; n = 5 – 7 mice per time point). Horizontal bars indicate mean values; statistical significance **$p < 0.01$; ***$p < 0.001$. **D.** Survival of mice primed with LP or PBS days -14 and -7 and challenged with PVM 13 weeks (91 days) later; n = 10 mice per group, **$p < 0.01$.

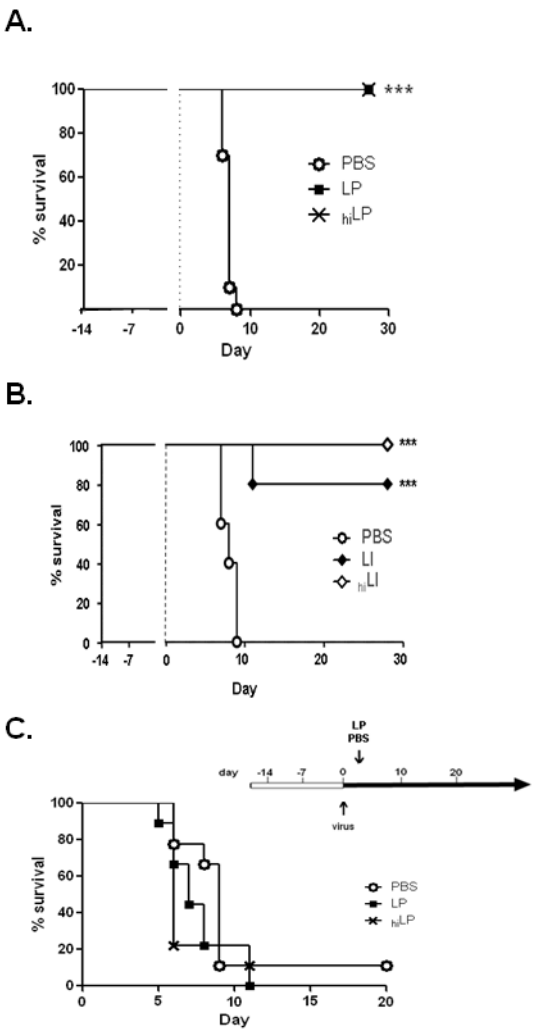

Figure 2. Priming of the respiratory mucosa with heat-inactivated lactobacilli and other gram-positive bacteria

Standard experimental protocol is as per Fig. 1A unless otherwise noted. **A.** Survival of mice inoculated with LP, heat-inactivated (hi) LP (10^9 cfu-equivalents) or PBS prior to virus infection; **B.** Survival of mice inoculated with 10^9 cfu *Listeria innocua* (LI), 10^9 cfu-equivalents heat-inactivated *L. innocua* (LI), or PBS prior to virus infection; **C.** Survival of naïve BALB/c mice inoculated with PVM on day 0, then inoculated with lactobacilli (10^9 cfu LP, 10^9 cfu-equivalents heat-inactivated (hi) LP, or PBS + BSA) on day 3. Each group includes 10 or more mice per condition, representative of at least two independent experiments ***$p < 0.001$.

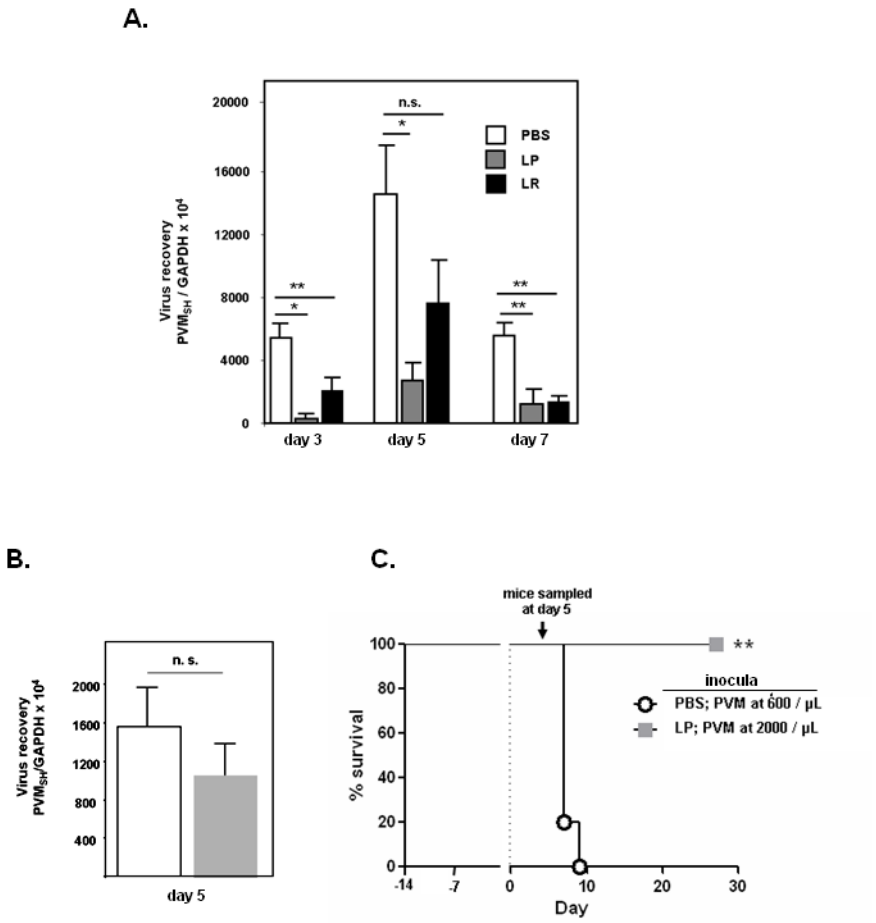

Figure 3. Virus recovery from lung tissue of *Lactobacillus*- and control-primed mice

A. Virus recovery from lung tissue at days 3, 5 and 7 after inoculation with PVM from mice treated with either *Lactobacillus* spp. or PBS + BSA control, as determined by qRT-PCR with two standard curves [Suppl. Fig. 1]; n = 5 – 7 mice per timepoint per condition, *$p <$ 0.05; **$p < 0.01$; n.s., not significant. **B.** and **C.** Survival of and virus recovery from *Lactobacillus* (LP) and PBS + BSA-primed mice. The virus (PVM) inoculum received by ten PBS + BSA -primed mice was reduced to 600 copies/µL so that peak recovery at day 5 would be comparable to that detected in the ten LP-primed mice. Virus recovery was evaluated in 5 mice selected randomly on day 5 from each group as shown, and % survival of 5 mice remaining is as shown; **p < 0.01.

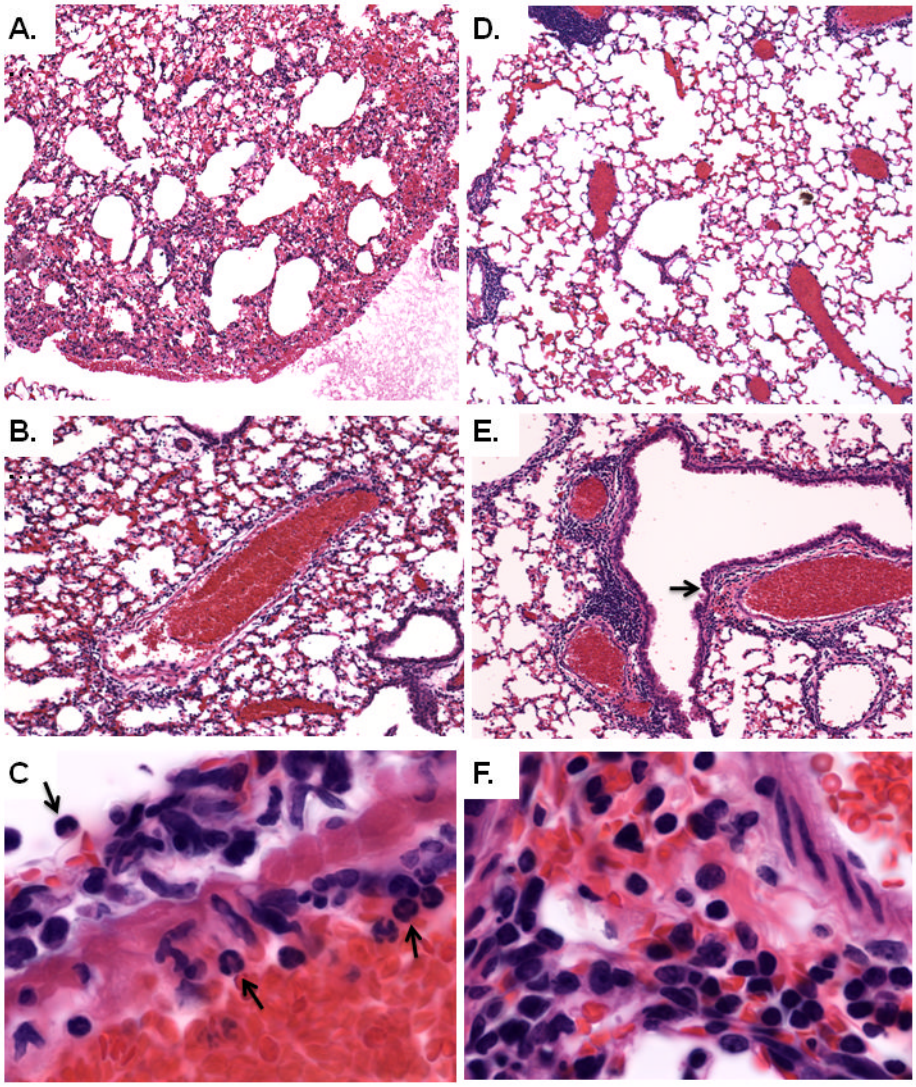

Figure 4. Histopathologic analysis

Hematoxylin and eosin-(H&E) stained lung tissue from mice primed with PBS + BSA (**A.**, **B.**, and **C**.) or *L. plantarum* in PBS + BSA (**D.**, **E.**, and **F**.) prior to virus infection; shown here at day 7 as per Fig. 1A. **A.** and **B**. Diffuse alveolar, bronchiolar, and perivascular inflammation is observed in lung tissue from PVM-infected, control-primed mice (original magnifications, 5X, and 10X, respectively). **C.** Arrows indicate infiltrating granulocytes (original magnification, 40X) seen exiting from the blood vessel in the center of the field in panel B. **D.** and **E.** Lung tissue from *L. plantarum*-primed, PVM-infected mice exhibits diminished alveolar inflammation and pronounced peribronchiolar and perivascular cuffing (original magnifications, 5X and 10X, respectively). **F.** Enlarged from E. (at arrow) dense lymphocyte-enriched inflammatory infiltrate, consistent with descriptions of induced bronchus-associated lymphoid tissue (iBALT; original magnification, 40X.)

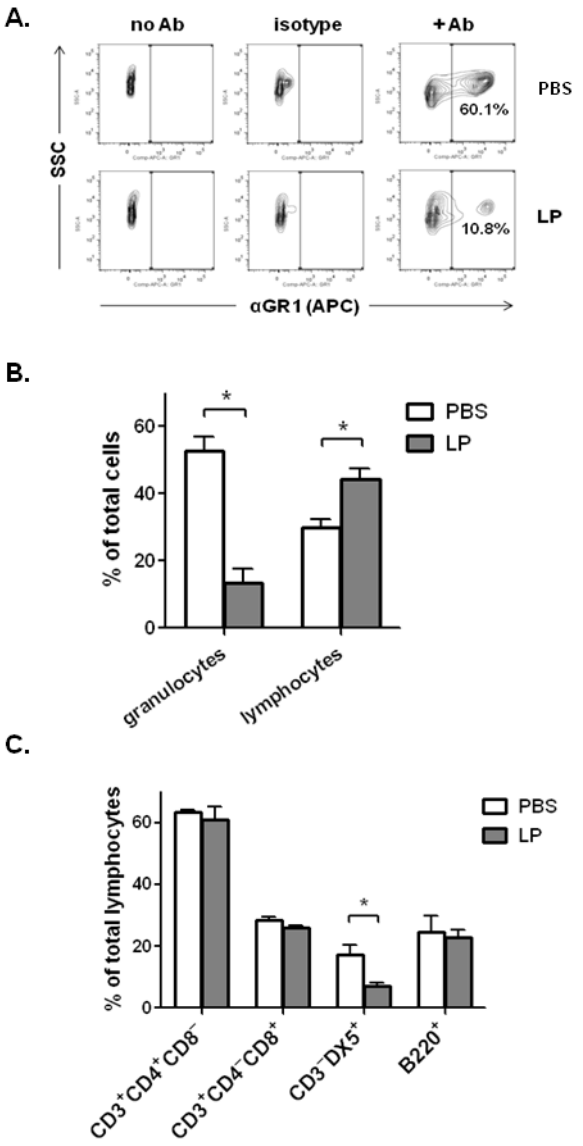

Figure 5. Flow cytometric analysis of leukocyte subsets

A. Flow cytometric analysis of whole-lung single-cell suspensions generated from control- (PBS + BSA) or *L. plantarum* (LP)-primed, PVM-infected mice (day 7, n = 5 – 6 mice per condition). Total lung cells were gated for side-scatter (SSC) and expression of the cell surface granulocyte marker GR1, shown with no-antibody and isotype-matched antibody controls. Data shown are representative of four independent experiments. **B.** Percentage of total viable lung cells identified as granulocytes ($GR1^+$) or lymphocytes (identified by characteristic forward/side scatter) from PBS + BSA-primed, PVM-infected or *L. plantarum*-primed, PVM-infected mice. **C.** Percentage of total viable lymphocytes (in B.), with $CD4^+$ T cell ($CD3^+CD4^+CD8^-$), $CD8^+$ T cell ($CD3^+CD4^-CD8^+$) NK cell ($CD3^-DX5^+$) or B lymphocyte ($B220^+$) immunophenotype; * = $p < 0.05$; ** = $p < 0.01$. Data shown are compiled from four independent experiments.

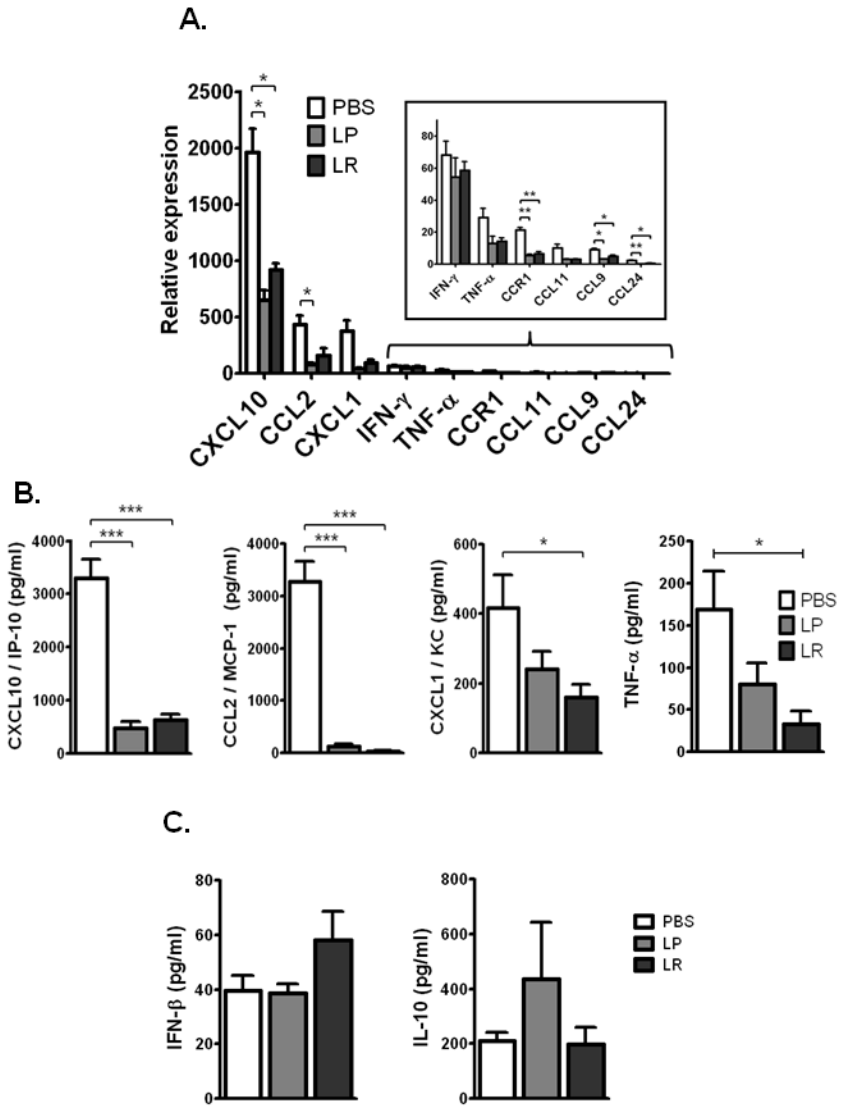

Figure 6. *Lactobacillus*-mediated priming of the respiratory mucosa leads to suppression of multiple virus-induced proinflammatory cytokines

A. Expression of transcripts encoding proinflammatory mediators in lungs of *Lactobacillus*- or PBS-primed, PVM-infected mice, normalized to expression in *Lactobacillus*- or PBS-primed, uninfected mice, respectively (day 7 as per Fig. 1A, n = 4 mice per experimental group; data compiled from three independent experiments). **B.** Immunoreactive CXCL10, CCL2, CXCL1, and TNF detected in BAL fluid of *Lactobacillus*- or PBS-primed, PVM-infected mice; **C.** Immunoreactive IFN-β and IL-10 detected in BAL fluid of *Lactobacillus*- or PBS-primed, PVM-infected mice; n = 4 – 5 mice per experiment; data compiled from three independent experiments; * $p < 0.05$; ** $p < 0.01$; ***$p < 0.001$; LP, *L. plantarum*; LR, *L. reuteri*.

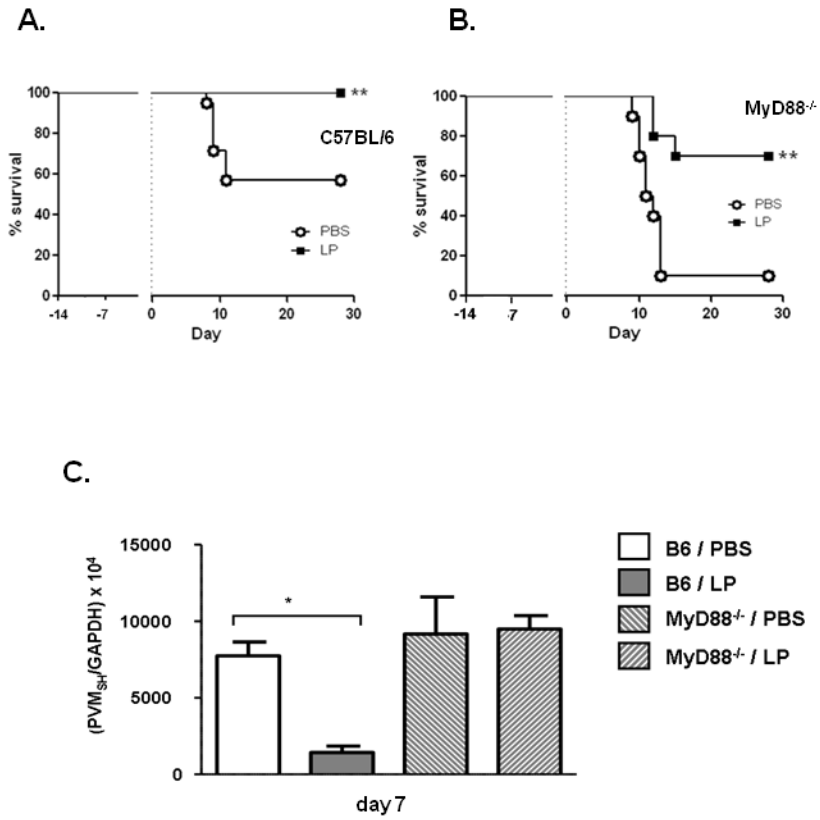

Figure 7. *Lactobacillus*-primed *MyD88* gene-deleted (*MyD88*$^{-/-}$) mice are also protected against the lethal sequelae of PVM infection

A. Survival of C57BL/6 mice primed with 10^9 cfu *L. plantarum* or PBS + BSA prior to PVM infection; n = 20 mice per group. **B.** Survival of *MyD88*$^{-/-}$ mice primed with 10^9 cfu *L. plantarum* or PBS + 1% BSA control prior to PVM infection; n = 8 – 10 mice per group. Data shown are representative of three independent experiments, ** = $p < 0.01$; LP = *L. plantarum*. **C.** Virus recovery from lung tissue determined by qRT-PCR of *L. plantarum*-primed and PBS-primed C57BL/6 and *MyD88*$^{-/-}$ mice on day 7 after PVM infection (as per Fig. 1A); n = 5 – 8 mice per timepoint per condition, *$p < 0.01$; data compiled from two independent experiments.

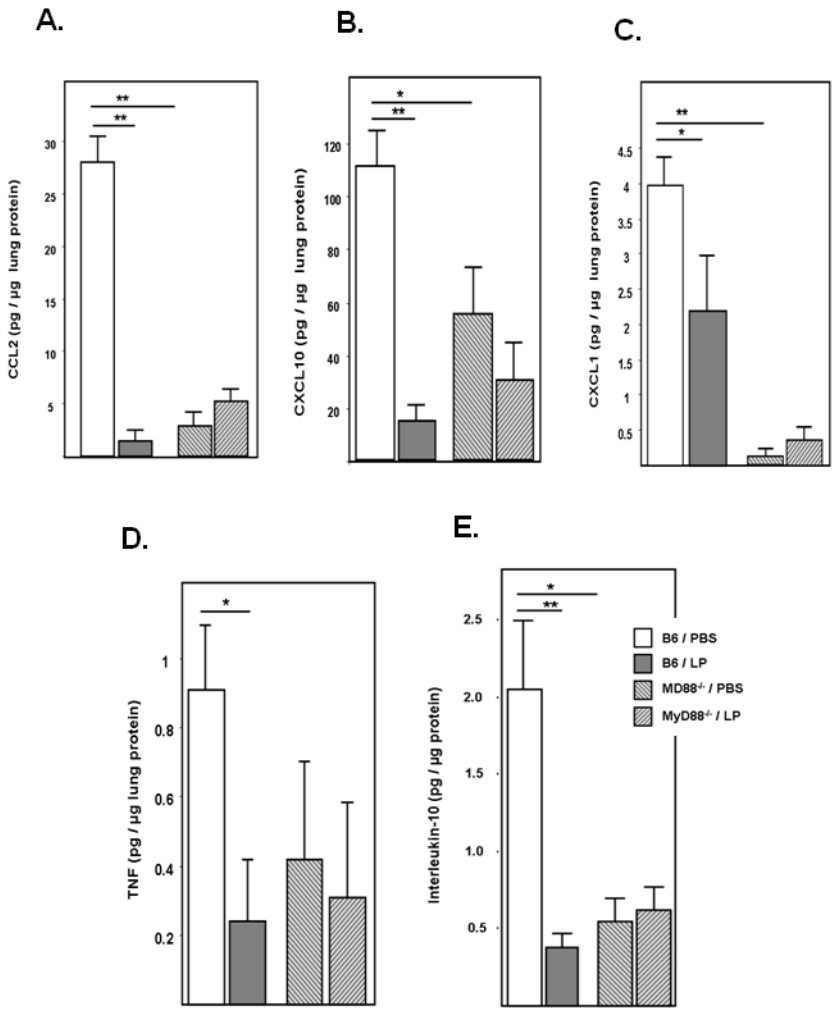

Figure 8. *Lactobacillus*-priming of *MyD88*$^{-/-}$ mice has no impact on virus-mediated production of inflammatory cytokines

Immunoreactive **A.** CCL2, **B.** CXCL1, **C.** CXCL10, **D.** IL-10, and **E.** TNF detected in lung tissue homogenates from C57BL/6 and *MyD88*$^{-/-}$ mice at day 7 after virus infection; n = 5 – 8 mice per time point per condition, *$p < 0.05$; **$p < 0.01$; data compiled from two independent experiments.

Table 1

Survival of *L. plantarum* (LP)-primed BALB/c mice inoculated with PVM on day 0 as per standard protocol [Fig. 1A] or delayed seven, twenty-one or ninety-one days thereafter. Survival was determined at t = 30 days after each virus inoculation. All surviving mice (29 of a total 34) underwent seroconversion to PVM antigens (SMART-M12, see Methods).

Virus inoculation on	day 0	day 7	day 21	day 91
Survival	8/8 (100%)	7/8[a] (88%)	8/8 (100%)	6/10 (60%)

[a]The single death among the mice inoculated on day 7 occurred 8 days after PVM inoculation. The full survival analysis of the mice inoculated 91 days after *Lactobacillus* priming is shown in Figure 1D.