Dietary Bovine Lactoferrin Reduces *Staphylococcus aureus* in the Tissues and Modulates the Immune Response in Piglets Systemically Infected with *Staphylococcus aureus*

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Supplementary Material: Supplemental Tables 1-3 are available from the “Online Supporting Material” link in the online posting of the article and from the same link in the online table of contents at [http://cdn.nutrition.org](http://cdn.nutrition.org).
Abbreviations used: BI, group receiving *B. infantis*; *Bifidobacterium longum biovar infantis*, *B. infantis*, bLF, bovine lactoferrin; CFU, colony forming units; CON, control formula group; COMB, piglets fed bLF and receiving *B. infantis*; LF, bLF formula group; *Staphylococcus aureus*, *S. aureus*; TLR2, toll-like receptor 2
**ABSTRACT:**

**Background:** Bovine lactoferrin (bLf) reduces *Staphylococcus aureus* infection in premature infants and promotes the growth of *Bifidobacterium infantis*, a predominant infant gut species. We hypothesized bLf in combination with *B. infantis* would reduce the severity of systemic *S. aureus* infection.

**Objective:** To determine the effects of oral administration of bLf and *B. infantis* on the course of systemic *S. aureus* infection.

**Methods:** Colostrum-deprived piglets consumed formulas containing 4g/l whey (CON) or bLf (LF). Half were gavaged with *B. infantis* (10⁹ CFU/d) resulting in two additional groups (BI or COMB). On d7, piglets were intravenously injected with *S. aureus*. Blood samples were collected pre-infection and every 12h post-infection for immune analyses. Tissue samples were collected on d12 for analysis of bacterial abundance and gene expression.

**Results:** Pre-infection, LF piglets had lower serum IL-10, higher percent lymphocytes and lower percent neutrophils than BI or COMB. After infection, dietary bLf increased piglet weight gain, reduced staphylococcal counts in kidney and tended to lower staphylococcal counts in lung and heart. Dietary bLf also decreased kidney IL-10 and increased lung IFNγ mRNA. *B. infantis* increased splenic IFNγ expression. Renal toll-like receptor 2 was upregulated in BI piglets, but not in COMB piglets. Post-infection, BI piglets had increased serum IL-10 and decreased memory T cell populations. LF and COMB piglets had fewer circulating monocytes and B-cells than CON or BI piglets.

**Conclusions:** Dietary bLf and *B. infantis* produced independent and tissue-specific effects. Piglets fed bLf alone or in combination with *B. infantis* mounted a more effective immune response and exhibited lower bacterial abundance, whereas *B. infantis* administration was
associated with greater tissue bacterial abundance. This study provides biological underpinnings
to the clinical benefits of bLf observed in preterm infants, but does not support \emph{B. infantis}
administration during \emph{S. aureus} infection.

\textbf{Key Words:} lactoferrin, infection, probiotic, immune system, sepsis, neonate
INTRODUCTION

*Staphylococcus aureus* infection is the most common fatal bacterial infection in neonates worldwide (1). The infection can result in endocarditis, pneumonia, osteomyelitis, and septic shock (2). In recent years, antibiotic-resistant strains of *S. aureus* have emerged, limiting treatment options for life-threatening *S. aureus* infections in infants (2). A clinical trial (3) and subsequent meta-analysis (4) showed that orally-administered bovine lactoferrin (bLf) reduced the incidence of late-onset sepsis in very low birth weight infants colonized with gram-positive bacteria, including *Staphylococcus* species (3).

The role of lactoferrin in the immune response and infection has recently been reviewed (5, 6). These effects likely occur in the intestinal lumen as well as through direct effects on immune cells as bLF is resistant to proteolytic digestion (7, 8) and because both piglet and human intestinal epithelial cells express lactoferrin receptors (9-11). Although the mechanism of action whereby dietary bLf reduces *S. aureus* infection is unknown, several modes of action are plausible. First, lactoferrin is an iron-binding glycoprotein, which may exert antimicrobial effects by preventing microbes from accessing adequate iron. Lactoferrin is also released by neutrophils at the sites of injury or infection. The release of lactoferrin inhibits infiltration of inflammatory neutrophils while attracting monocytes, suggesting that lactoferrin plays an important role in regulating inflammation thereby preventing sepsis without inhibiting the original immune response (12). In addition to having effects on the early immune response, reports in the literature suggest that lactoferrin is important in generating a Th1 adaptive immune response in mice (13, 14) and piglets (15). A Th1 adaptive response would favor a cellular-immune response to intracellular *S. aureus* that would increase bacterial clearance from tissues. Lactoferrin also promotes the growth of beneficial commensal bacteria of the *Bifidobacteria* spp., especially *Bifidobacterium infantis* (16). Foxp3 expressing intestinal and splenic T regulatory cells were
increased in *B. infantis*-fed mice (17) and humans (18). This evidence suggests that lactoferrin and *B. infantis* may act synergistically to influence regulatory immune function in addition to having independent effects on the innate and adaptive immune responses resulting in an improved immune response to a pathogenic challenge.

This study was designed to analyze the immune response to a systemic *S. aureus* infection in piglets fed bLf alone, *B. infantis* alone, or bLf and *B. infantis* in combination. Because bLf and *B. infantis* promote key innate and adaptive immune responses, we hypothesized that bLf in combination with *B. infantis* would be more efficacious at improving the anti-bacterial immune response and bacterial clearance during a blood-borne infection than either bLF or *B. infantis* alone.

**MATERIALS and METHODS**

*Animal Protocol and Diets*

All animal care and experimental procedures were approved by the Institutional Animal Care and Use Committee at the University of Illinois. Pregnant sows (n=15) at the University of Illinois Swine Research Center were monitored for farrowing beginning on d110 of gestation and female piglets (n=49) were removed prior to ingestion of colostrum. Due to the close proximity of the umbilicus and urethral opening in male piglets, females were selected to avoid soaking of bandages and urethral catheters with urine. Piglets were randomized to treatment group based on birth weight and litter. All pigs weighed ~1.5kg at birth. To provide passive immunity, sow serum was administered to the piglets via oral gavage at a volume of 5 ml/kg BW at birth, 12, 24 and 36h postpartum. Piglets were individually housed in cages in environmentally-controlled rooms (25°C). Plastic heating pads in each enclosure were used to maintain an ambient
temperature of 30°C. Piglets were fed a non-medicated, sow-milk replacer formula (Liqui-Wean Advance, Milk Specialties Global Animal Nutrition, Carpentersville, IL) with either 4g/l of supplemental protein as whey protein (CON; Provon 192; Glanbia) or bLf (LF; Bioferrin 200; Glanbia, Kilkenny, Ireland). This dose of bLf was chosen based on our previous research (15, 19) and whey was added to the CON diet to keep the diets isonitrogenous. Piglets were fed 20-times daily totaling 360 ml/kg BW/d. Half of the piglets in each group were further randomized to receive Bifidobacterium longum biovar infantis (B. infantis; 3 x 10⁹ CFU/day): Whey + B. infantis (BI) and bLf + B. infantis (COMB). Resulting in four treatment groups: LF, CON, BI, COMB.

B. infantis Preparation, Storage, and Administration

B. infantis ATCC 15697 (ATCC, Manassas, VA) was grown from a frozen stock in deMan, Rogosa, Sharpe broth (Difco, Livonia, MI) supplemented with cysteine (0.05%) and incubated anaerobically as previously described (20). Mid-exponential phase B. infantis was harvested by centrifugation, resuspended in sterile PBS and cryogenically preserved in a 1:1 cell to glycerol (25%) suspension. Each batch of B. infantis inoculum was validated for viability on Reinforced Clostridial Agar. On average, each stock contained 5 x 10⁸ colony forming units (CFU) per ml. Prior to administration, B. infantis was washed in PBS, and the bacterial pellet was resuspended in PBS for administration. Piglets in the BI and COMB groups were orally gavaged with 2 ml of the washed B. infantis thrice daily for a total dosage of ~3 x 10⁹ CFU/day. This dose was selected based on typical probiotic dosing regimens (21-23).
Piglets underwent a surgical procedure within 12 h of birth to place two umbilical catheters using established methods (24). One catheter was used for administering the *S. aureus* and the other for blood sampling. Briefly, piglets were lightly sedated with 2% isoflurane (IsoFlo, Abbott Laboratories, North Chicago, IL). The abdomen was washed and an iodine disinfectant applied to the umbilicus and surrounding region. To numb the umbilicus, lidocaine (Henry Schein, Melville, NY) was injected subcutaneously into multiple sites surrounding the umbilical stump. One catheter (3.5 french polyvinyl chloride catheter; Tyco Healthcare Group, Mansfield MA) was inserted 22 cm into the dorsal aorta to a position near the heart. A second catheter for blood sampling was inserted and advanced 20 cm. Catheters were sutured to the umbilical stump and secured to the body with suture and elastic tape. Piglets were fitted into a jacket to protect the catheterization site while allowing free movement within the cages. Catheter patency was maintained by flushing twice daily with heparinized saline (10 IU heparin/ml in 0.9% NaCl). Piglets received one systemic dose of Enrofloxacin (2.5 mg/kg; Bayer, Shawnee Mission, KS) immediately after surgery.

*S. aureus Infection*

*S. aureus* strain S54F9 was a gift from Dr. Bent Aalbaek, (University of Copenhagen, Denmark) (25). *S. aureus* was cultured in Brain Heart Infusion broth aerobically at 37°C. Prior to administration, stationary phase *S. aureus* cells were harvested by centrifugation, resuspended in 0.9% sterile isotonic saline and diluted to $10^5$ CFU/ml. On d7, all animals were administered *S. aureus* at 1ml per kg body weight via the umbilical catheter. This dose was chosen based on a
pilot study in which the temporal clinical signs and immune responses to two *S. aureus* doses (10^3 and 10^5 CFU) were evaluated compared to non-infected piglets (26).

**Sample Collection**

Body weight and formula intake were assessed daily. Rectal temperature and activity were assessed every 12h post-infection. Blood samples were collected into non-heparinized vacuum tubes via the sampling umbilical catheter prior to infection and every 12h post-infection for cytokine analyses. Heparinized blood was collected at 72h and 120h post-infection for PBMC isolation. Prior to infection and at 120h post-infection, fresh blood smears were collected for complete blood counts (CBC)(Clinical Pathology Laboratory, Hematology Department, University of Illinois College of Veterinary Medicine, Urbana, IL). At 120h post-infection, piglets were euthanized by an intravenous injection of sodium pentobarbital (72 mg/kg BW, Fatal Plus, Vortech Pharmaceuticals, Dearborn, MI).

**Measuring *B. infantis* in Ascending Colon Contents and Feces**

**DNA Extraction**: Total genomic DNA was isolated from ascending colon (AC) contents and feces using a combination of bead beating and the QIAamp Fast DNA Stool Mini Kit (Qiagen, Germantown, MD). Approximately 200 mg of AC or feces was combined with 1 ml of InhibitEx buffer in a 2 ml Lysing Matrix B tube. Tubes were shaken at 6 m/s for 30s using the Fastprep 24 System (MP Biomedicals, Solon, OH). Samples were incubated at 95°C for 5 min and centrifuged at 20,800 x g for 1 min. DNA was purified from 200 μl of supernatant using the QIAMP Fast DNA Stool Mini Kit according to the manufacturer's instructions. Isolated DNA
was quantified with a NanoDrop 1000 spectrophotometer (Thermo Fisher Scientific, Wilmington, DE).

RT qPCR: The absolute abundance of *B. infantis* in AC contents and feces was quantified by qPCR using primers BiINF-1 and BiINF-2 (27). PCR was performed with an Applied Biosystems 7900HT Fast Real-Time PCR System using SYBR Green assays. PCR was run in triplicate with a reaction volume of 10 µl: 5 µl of 2X Power SYBR Green PCR Master mix (Applied Biosystems), 1 µl bovine serum albumin (1mg/ml, New England Biolabs, Ipswich, MA), 0.5 µM of each primer and 10 ng of template DNA. The cycling conditions were 50°C for 2 min, 95°C for 10 min, followed by 40 cycles of 95°C for 15s, 55 °C for 20s and 72°C for 60s. Following amplification, a dissociation step was included to analyze the melting profile of the amplified products. Standard curve (10²–10⁷ 16S rRNA gene copies per reaction) was generated using purified pCR 4 TOPO-TA plasmids (Thermo Fisher Scientific) containing the 16S rRNA genes of *B. infantis*. Data were processed with SDS v2.3 software (Thermo Fisher Scientific).

**Flow Cytometry to Identify PBMC subpopulations**

PBMC were obtained by Ficoll-Hypaque centrifugation of heparinized blood. Cells were resuspended in flow staining buffer (PBS, 1% BSA, 0.1% sodium azide). Cell populations were assessed by flow cytometry using fluorescently-labeled antibodies as described (28). Cell staining antibody cocktails are presented in **Supplemental Table 1** (online).

T lymphocyte populations were expressed as a percent of CD3+ events for CD3⁺CD4⁺CD8⁻ (T helper cells) and CD3⁺CD4⁺CD8⁺ (Cytotoxic T cells) and CD3⁺CD4⁺CD8⁺ (Memory T cells). NK cells were identified as CD3⁻CD4⁻CD8⁺ events and expressed as a percent of CD3⁻ events. Monocytes were identified as CD14⁺CD163⁺CD172a⁺ events and expressed as a percent of
CD172a⁺ events. B cells were identified as CD21⁺MHCII⁺ events and expressed as a percent of total lymphocytes.

Serum Cytokines

Serum was obtained by centrifugation of blood samples and was analyzed using porcine-specific ELISA kits for interferon-gamma (IFNγ) (limit of detection [LOD]: 62.5 pg/ml), IL-6 (LOD: 125 pg/ml) and IL-10 (LOD: 23.4 pg/ml) (R&D Systems, Minneapolis, MN). IL-10 was measured in blood samples taken pre-infection and every 12 h post-infection. IFNγ was measured in blood samples taken pre-infection and 24, 36 and 72h post-infection. IL-6 was measured in blood samples taken pre-infection and 72h post-infection. For samples with concentrations below the LOD of the assay (the lowest point on the standard curve), the value was set to one-half the LOD (29).

Detecting S. aureus in Blood and Tissue Samples

Immediately after euthanasia, blood was collected by cardiac puncture into heparin-laced vials. Five grams of whole organ cross sections for the kidney (each section included: left, cortex and medulla), lung (each section included: left, caudal lobe), heart (each section included: apex, left and right ventricles) and spleen were collected. Tissues were homogenized at a 1:5 dilution in sterile PBS using a stomacher (Stomacher 80 Biomaster, Seward Laboratory Systems Inc., Port St. Lucie, FL). For each tissue sample, three cultures were started on mannitol salt agar (MSA) (BD, Franklin Lakes, NJ), a selective and differential media for S. aureus: 200 µl was hand-plated at 1:5, 50 µl was spiral plated (Neu-Tec Group Inc., Farmingdale, NY) at 1:5, and 50
µl was spiral plated at 1:10. Blood samples were plated undiluted on MSA. All tissue samples were plated in triplicates at each dilution. Plates were incubated for 48h aerobically at 37 °C before being counted. Colony counts were averaged for each set of triplicates and corrected for the dilution factor. Final results for *S. aureus* load are expressed as CFU/g of tissue.

**Tissue Cytokine Analysis**

**RNA Extraction:** Frozen kidney, lung and spleen samples (100 mg) were homogenized with 1 mL of TRIzol reagent per the manufacturer’s instructions (Thermo Fisher Scientific). RNA was dissolved in 20 µl of nuclease-free water (Thermo Fisher Scientific) and quantified using a NanoDrop 1000 instrument (Thermo Fisher Scientific). Samples were diluted to an RNA concentration of ≤500 ng/µl, and RNA quality was determined using a 2100 Bioanalyzer (Agilent Technologies, Inc., Santa Clara, CA).

**RT qPCR:** Samples with an RNA integrity number (RIN) > 6 were transformed into cDNA utilizing a high-capacity cDNA reverse transcription kit (Thermo Fisher Scientific). PCR was performed using TaqMan gene expression assays for *IFNG* (Ss03391053_g1), *IL10* (Ss03382372_u1) and *TLR2* (Ss03381278_u1). The expression of the 60S ribosomal protein L19 (*RPL19*; Ss03375624_g1) gene was used as an endogenous control. The relative standard curve method was used for quantitation. Standard curves consisted of dilutions of cDNA created from spleen mRNA pooled from animals in all of the treatment groups. Normalized values for each target were calculated by dividing the target quantity mean by the RPL-19 quantity mean. A fold-difference was calculated for each measurement by dividing the normalized target values by the normalized calibrator sample. Animals fed whey (CON) were used as the calibrator in each instance.
Statistical analyses were performed using SAS Version 9.2 (Cary, NC). Body weight, rectal temperatures, serum cytokines and immune cells were compared among groups by repeated-measures ANOVA using PROC MIXED with treatment (bLf or no bLf), probiotic (received or did not receive *B. infantis*) and time as fixed effects. The model also included all interactions treatment by time, treatment by probiotic, and probiotic by time. Because some pre-infection measurements were missing, CBC/differential data were analyzed by 1-way ANOVA (treatment) using PROC GLM. RT qPCR data was analyzed by 1-way ANOVA (treatment) using PROC GLM. The statistical model for this data included fixed effects for treatment (bLf or no bLf), probiotic (received or did not receive *B. infantis*), and the interaction between treatment and probiotic. Staphylococcal load was analyzed using a nonparametric Wilcoxon Rank Sum on CFU/g, where the one-sided Z-statistic was used due to a sample size greater than 10. In the event of a significant main effect, a post hoc Least Significant Difference test was used. The abundances of *B. infantis* are presented as means (Log_{10} copies/g of content) ± SD. The number of 16S rRNA gene copies was log_{10} transformed prior to analysis. To compare *B. infantis* abundance, statistical analysis was performed using the PROC MIXED procedure of SAS version 9.2 (SAS Institute) with Tukey post-hoc tests. Fixed effects included diet, probiotic and the interaction of diet and probiotic. Replicate was included as random effect. When the abundance of *B. infantis* was below the LOD (2 \times 10^5 copies of 16S rRNA genes/g of content), \( \frac{1}{2} \) value of the LOD was used. The occurrence of *B. infantis* among treatments was analyzed by Fisher’s exact test. Statistical significance was defined as P<0.05 and trends reported as P<0.10. Unless otherwise stated, data are presented as mean ± SEM.
RESULTS

Formula Intake, BW and Survival

All piglets were fed an additional 4g/l protein. CON and BI pigs received whey protein. LF and COMB pigs received bLf. Formula intake was unaffected by treatment or infection and averaged 793 ± 30 ml/d on d1-d7 and 1092 ± 27 ml/d following infection between d7-12 postpartum. Thus, mean supplemental protein intake was 4 g/day at d7 and 4.8 g/day at d12. Prior to infection all piglets had similar body weights. The addition of the probiotic *B. infantis* to either diet had no effect on body weight, therefore, values were pooled by bLf supplement: bLf-supplemented (LF and COMB) and non-bLf supplemented (CON and BI) (**Figure 1**). Following infection, bLF-supplemented piglets weighed more than non-bLf supplemented piglets (treatment x time, P<0.0001). At the end of the study, bLf-supplemented piglets weighed 3.7 ± 0.1 kg and non-bLf-supplemented piglets weighed 3.4 ± 0.1 kg (Figure 1). Four piglets died during the experiment (1 LF, 2 BI and 1 COMB) and were not included in the analyses. The LF piglet had failure to thrive throughout the experiment. The other three piglets died 1, 2 or 3 days post-infection. While these post-infection deaths could be attributed to the *S. aureus* infection, their growth and rectal temperatures post-infection did not differ from that of piglets that survived the study.

Rectal Temperature
Rectal temperatures peaked 36h post-infection and remained elevated until euthanasia at 120 h post-infection. *B. infantis* had no effect on rectal temperatures, so temperatures were pooled by bLf supplement: bLf-supplemented (LF and COMB) and non-bLf-supplemented (CON and BI). Post-infection, there was a significant overall effect where bLf-supplemented animals had greater rectal temperatures than non-bLf-supplemented piglets (P=0.01) with no interaction between protein supplement and hour. On average, post-infection rectal temperatures in bLf-supplemented pigs were 0.21°C higher than those of non-bLf-supplemented animals. Rectal temperatures differed by time (P<0.0001). All animals had elevated rectal temperatures at 36 h post-infection compared with baseline, 12 or 24h post-infection. All animals continued to have elevated rectal temperatures until euthanasia at 120h post-infection. At baseline, just prior to infection, animals had rectal temperatures of 39.2 ± 0.2, 39.1 ± 0.2, 39.0 ± 0.1, and 39.1 ± 0.1 °C for CON, BI, LF and COMB, respectively. At 36h post-infection, animals had rectal temperatures of 39.3 ± 0.1, 39.5 ± 0.2, 40.0 ± 0.2 and 39.7 ± 0.2 °C for CON, BI, LF and COMB, respectively.

Detection of *B. infantis* in AC and Feces

*B. infantis* was detected more frequently in the AC and feces from piglets inoculated with *B. infantis* than in non-inoculated pigs (94.4% vs 4.2% in AC; 100% vs. 5% in feces; P < 0.0001) (Supplemental Table 2). The occurrences of *B. infantis* were similar in BI and COMB (the treatment groups that included probiotic) pigs. The occurrences *B. infantis* were significantly higher in BI and COMB pigs compared to CON and LF (the treatment groups without probiotic) pigs in both sampling sites. Bovine Lf had no effect on the abundance of *B. infantis*. *B. infantis* abundance was greater in both AC and feces of BI (7.0 ± 1.1 and 7.2 ± 1.0 log_{10} copies/g,
respectively) and COMB (7.5 ± 1.4 and 7.4 ± 1.0 log10 copies/g, respectively) compared to CON and LF (\textit{B. infantis} was detected in only one LF AC sample and one CON fecal sample). In both AC and fecal samples, the abundance of \textit{B. infantis} did not differ between BI and COMB groups.

Peripheral Blood Cell Populations

Blood cell populations were assessed pre- and 120h post-infection using cell counts from whole blood smears. \textit{B. infantis} administration had no effect on whole blood cell populations. However, bLf influenced circulating cell populations (Supplemental Table 3). Prior to infection, the peripheral blood from bLf-supplemented animals (LF and COMB) had more lymphocytes and tended to have fewer neutrophils than the blood from non-bLf-supplemented animals (CON and BI). Post-infection, only one pig (in the BI group) met the immature-to-total neutrophil ratio cut-off (>0.25) indicative of sepsis (30). On average, bLf-supplemented piglets had 43 ± 3.7% and non-bLf-supplemented piglets had 31 ± 3.0% blood lymphocytes. bLf-supplemented pigs had 53 ± 3.8% and non-bLf-supplemented pigs had 62 ± 3.4% blood neutrophils. Following infection, nucleated red blood cell (NRBC) populations were lower (P=0.047) in bLf-supplemented piglets compared to non-bLF-supplemented piglets. On average, NRBC were 3.5 ± 0.9% and 7.3 ± 1.7% of total blood cells in bLf-supplemented and non-bLF supplemented piglets, respectively.

Using peripheral blood mononuclear cells (PBMC) isolated by density gradient centrifugation, B cell, T cell, NK cell, and monocyte/macrophage cell populations were assessed at 72h and 120h post-infection.
B cell populations were similar for all piglets within each time point (Table 1). The percentage increase in PBMC B cells from 72h to 120h post-infection differed by protein supplement group, with bLf-supplemented piglets experiencing a smaller increase in B cell population size than CON piglets (P=0.04).

Monocyte populations were similar for piglets in all four treatment groups at both 72 and 120h post-infection (Table 1). The percent difference in PBMC monocytes from 72h to 120h post-infection in bLf-supplemented piglets tended (P=0.07) to be smaller than that in non-bLf-supplemented animals (Table 1).

T cell subpopulations: Neither T helper (70.2 ± 8.4%) nor cytotoxic T cell (5.3 ± 0.6%) populations differed among treatment groups at either time point. However, in an analysis measuring only the effect of treatment at 120h post-infection, memory T cell populations were smaller (P=0.03) in piglets receiving B. infantis than in piglets that did not receive the probiotic (Table 1). The percent difference in PBMC memory T cell populations from 72h to 120h post-infection in probiotic supplemented piglets was lower (P=0.03) than the percent difference in monocytes from 72 to 120h post-infection in non-probiotic-supplemented animals.

NK cell populations were similar for all piglets at each timepoint, but NK cell populations were larger 120h post-infection (5.8 ± 1.0%) than 72h post-infection (2.6 ± 0.4%).

Serum Cytokines

Of the three serum cytokines analyzed, only IL-10 was detected in the serum of piglets at multiple time points. Neither IFN-γ nor IL-6 was detectable in piglets prior to infection nor were these two cytokines detectable in the majority of piglets at 72h post-infection. Prior to infection on postpartum d7, there was no effect of probiotic, therefore data were pooled by bLF (LF and
COMB) vs non-bLf (CON and BI)-supplemented piglets. Piglets fed formula with bLf had 3-fold lower (P=0.01) serum IL-10 than non-bLf-supplemented piglets (Figure 2a). Following infection, serum IL-10 concentrations changed significantly over time (P= 0.03). The highest concentrations of IL-10 were observed at 96h (58.2 ± 24.0 pg/ml) and 108h (45.4 ± 16.7 pg/ml) post-infection (Figure 2b). There was no effect of bLf on serum IL-10 post-infection. Therefore, data were pooled by probiotic treatment. Probiotic-treated animals (BI and COMB) had higher serum IL-10 (P=0.03) concentrations than piglets that did not receive B. infantis (Figure 2b).

*S. aureus in blood and tissues*

**Bacterial number:** *S. aureus* was detected in the kidneys, lungs, hearts and spleens, but not in the blood. There was no effect of BI on *S. aureus* content in blood or tissues, therefore data was pooled by bLf supplement (Figure 3). bLf-supplemented pigs had lower numbers (CFU) of *S. aureus* in the kidney (P=0.02) and tended to have lower numbers in lung (P=0.07) and heart (P=0.06) compared to piglets who consumed diets without bLf. There was no effect of bLf on *S. aureus* numbers in the spleen. Overall, dietary bLf decreased kidney, lung and heart *S. aureus* load by 7.3-, 4- and 1.8-fold, respectively.

**Immune Gene Expression in the Tissues**

**Kidney:** Piglets exposed to *B. infantis* in the context of a whey protein diet (BI) had the highest (P=0.01) kidney TLR2 mRNA expression. However, piglets exposed to *B. infantis* in the context of a bLf diet (COMB) had renal TLR2 mRNA expression similar to that of CON or LF piglets (Table 2). Pigs consuming diets with bLf (LF and COMB) had decreased renal IL-10 expression (P=0.03). Piglets receiving *B. infantis* in the absence of dietary bLf (BI) tended
(P=0.09) to have the highest renal IL-10 expression. Renal IFN\(\gamma\) expression was similar in all piglets.

**Lung:** IFN\(\gamma\) expression was significantly higher in LF and COMB piglets compared to CON and BI piglets (Table 2). No significant differences in TLR2 or IL-10 mRNA expression in the lung were observed.

**Spleen:** Piglets exposed to *B. infantis* had higher (P=0.02) splenic IFN\(\gamma\) mRNA expression (Table 2) than piglets that were not given the probiotic. Splenic TLR2 and IL-10 mRNA expression was similar in all piglets.

**DISCUSSION**

The goal of this study was to investigate the individual and combined effects of bLf and *B. infantis* on the clinical course of a systemic *S. aureus* infection in the neonatal piglet. This research was predicated on previous clinical trials demonstrating the orally-administered bLf reduced the incidence of late-onset sepsis in very low birth weight infants colonized with gram-positive bacteria, including *Staphylococcus* species (3). Furthermore, *B. infantis* has been shown to be immunomodulatory (17, 31) and bLf may promote the growth of *B. infantis* (16), suggesting the potential for synergistic effects. Based on our previous research (15, 19), by the 7th day of life, bLf improved gastrointestinal development and immune system development compared to piglets fed formula alone. Thus, these early effects on the gastrointestinal and immune systems likely give the bLf-fed piglets an advantage over their formula fed peers upon systemic challenge with *S. aureus*.

Despite promising clinical outcomes, the immune response is difficult to assess in human infants, thus the systemic and tissue immune responses over the course of *S. aureus* infection
were assessed using the newborn piglet. The piglet is an excellent preclinical model for this research for the following reasons: *S. aureus* is a dominant cause of widespread septicemia in pigs and humans (32); swine physiology, immune response and anatomy are highly similar to those of humans (33); and, most importantly, pigs are capable of reproducing the gradual pathophysiologic changes and clinical characteristics of neonatal sepsis (34), including body weight and temperature, which are easily monitored in piglets. The use of bLf in this appropriate pre-clinical model for human infants was deliberate as this is the same compound that can used in human infant formulas. In the current study, dietary bLf and *B. infantis* each influenced the response to *S. aureus* infection in the neonatal piglet, but the combination of bLf and *B. infantis* did not exert synergistic effects. Overall, the severity of *S. aureus* infection was reduced in piglets fed dietary bLf, with limited beneficial effects of *B. infantis*.

Dietary bLf improved weight gain following *S. aureus* infection. The beneficial effect of bLf on growth cannot be attributed to the presence of additional protein, as the CON and BI diet were supplemented with 4 g/l whey protein to maintain similar protein content to the LF and COMB diets (supplemented with 4g/l bLf. Previous studies have shown that bLf improves weight gain in piglets (35) and human infants (36). The increase in body weight has been partially attributed to its proposed role in regulating the immune system and providing protection against microbial infection. Wherein, animals that more effectively respond to infection have a reduced period of cachexia and can apportion more energy toward growth versus directing that energy toward a sustained immune response.

A key finding of this study was that dietary bLf significantly reduced bacterial abundance in the kidneys and tended to lower the *S. aureus* counts in the lungs and hearts of infected animals. The improved bacterial clearance in the presence of bLf was likely due in part to an enhanced
Th1 immune response in bLf-supplemented pigs. In our study, bLf-supplementation increased IFNγ mRNA expression in lung following infection, indicating a Th1 response. Furthermore, bLf-supplemented pigs had less serum IL-10 on d7 post-partum just prior to *S. aureus* infection. A high level of IL-10 is known to inhibit Th1 immune responses (37). Others have shown that Lf-transgenic mice demonstrated an enhanced Th1 response to *S. aureus* infection. These mice showed greater IFN-γ response and increased ability to clear the bacterial infection (13).

Accordingly, *S. aureus* persistence was affected by dietary treatment. As in previous studies (25, 38), *S. aureus* was rapidly cleared from the blood of infected pigs but persisted in other tissues. Compared to supplementation with whey protein (CON, BI), supplementation with bLf (COMB, LF) significantly reduced *S. aureus* load. This was expected based on previous reports in rodents where bLf supplementation reduced *S. aureus* load in the kidneys of *S. aureus* challenged mice (14) and where Lf-transgenic mice demonstrated an increased ability to clear *S. aureus* following a challenge (13). Importantly, bLf-supplementation decreased *S. aureus* counts in the kidney and tended to decrease counts in the lung and heart.

In contrast, the probiotic *B. infantis* had no effect on bacterial clearance when administered alone. This may be related to increased TLR2 message and IL-10 message as well as IL-10 protein in these animals. *In vitro* work has shown that *S. aureus* down-regulates the inflammatory T cell response by triggering IL-10 production by monocytes via TLR2 activation (39, 40). The increased IL-10 dampens the immune response enabling *S. aureus* to colonize the host (40). Consistent with the IL-10 serum cytokine data, probiotic-treated animals also had fewer circulating memory T cells with significantly fewer memory T cells compared to non-probiotic-treated pigs at 120h post-infection. In the kidney, the enhanced TLR2 and IL-10 mRNA expression in response to probiotic treatment was decreased when bLf was present.
fact, the presence of bLf also decreased renal IL-10 message compared to the CON diet. However, as the effects were not consistent across tissues (kidney, lung, spleen, blood), other mechanisms may be at work. TLR2 signaling regulates additional inflammatory cytokine responses (41, 42), and S. aureus stimulates additional immune receptors so effects of bLf and B. infantis on other cytokines are also important. For instance, bLf-supplementation increased IFNγ expression in the lung. It is important to note that bLf may not only have decreased bacterial load, but also may have impaired S. aureus viability leading to these lower tissue counts.

We hypothesized that bLf would stimulate a robust Th1 immune response. Because B. infantis is known to down-regulate inflammatory responses (17), we hypothesized B. infantis would provide protection in the later phase of infection. In addition, bLf has been shown to promote growth of B. infantis in vitro (16), suggesting a potential mechanism by which these dietary components could synergize. In this experiment, bLf did not support the growth of B. infantis over that seen in pigs exposed to B. infantis in the absence of bLf. However, we observed that bLf-supplementation was most important for S. aureus bacterial clearance. Post-infection, B. infantis had an overall effect of increased serum IL-10, which is consistent with what has been observed in mice and humans supplemented with B. infantis (17, 18). High concentrations of IL-10 have consistently been shown to be a strong indicator of septic shock and predictor of mortality during infection due to its broadly immunosuppressive function (43).

Consistent with this, the only pig to have reached the diagnostic immature-to-mature neutrophil ratio for sepsis (44) was in the BI group. Furthermore, probiotic-treated pigs had higher post-infection NRBC counts. NRBCs are another cell population that has been associated with septicemia (45). It has been shown that in addition to promoting a Th1 response through increased IFNγ production, bLf can also increase the IL-12-to-IL-10 ratio in lipopolysaccharide
(LPS) stimulated splenocytes to promote the Th1 response (46). The presence of IL-12, a cytokine that promotes the Th1 response, in addition to IFNγ, leads to significantly decreased production of IL-10 (46). However, in our studies, we did not measure IL-12 and no IFNγ was detected in the serum. One possible explanation for this could be that IFNγ is an intracellular cytokine and its presence may be too low in the serum to detect. Previously, we found that spleen cells isolated from pigs fed bLf produced more IFNγ and TNFα than cells isolated from pigs fed a control diet (15). Although NK cells are the most likely potential sources of IFNγ, it may be that peripheral memory T cells contain intracellular IFNγ, both of these cells could release the IFNγ when needed during an immune response. Future experiments should use intracellular cytokine staining in combination with flow cytometry or ELISpot assays to determine the IFNγ production potential of cells isolated from areas local to the infection.

Despite the novelty of the model, the study described herein has several limitations. Neither iron status nor levels of bLf in stool and serum were measured. Therefore, the current study could not assess the fate of ingested bLf nor determine if the effects of bLf on S. aureus infection were due to bLf sequestration of iron from S. aureus. This study was designed to test the regulatory and adaptive immune response to S. aureus infection, based on the hypothesis that those would be the stages of the immune response during which the effects of combining probiotic and bLf treatment would be most efficacious at reducing the severity of S. aureus infection. Therefore, most details about the effects of the dietary treatments on the early immune response S. aureus infection are unknown. However, blood was collected pre-infection and every 12h post-infection for some analyses. IFN-γ was measured pre-infection and at 24, 36, and 72h post-infection. IL-6 was measured pre-infection and at 72h post-infection. These time points were chosen based on a pilot study. Because a limited volume of blood could be sampled (due to
piglet size and the repeated sampling design), blood was used for cytokine analyses rather than \textit{S. aureus} quantification at the early time points post-infection. Thus, conclusions about the effects of the dietary treatment on \textit{S. aureus} levels in the blood at early time points post infection cannot be drawn. Finally, although the presence of \textit{B. infantis} was determined in feces and ascending colon content, no attempt was made to test for \textit{B. infantis} in the blood or other tissues. Therefore, any effects that the potential translocation of the probiotic from the gut to the bloodstream could have on the immune response to infection are unknown. Future studies should measure bLf in fecal matter, serum and urine, and should carefully assess the iron status (ferritin, transferrin, free iron) of subjects. Additional studies, should also examine the effects of probiotic and bLf on early inflammatory and innate immune responses to infection. This preliminary animal study provides mechanistic insight supporting clinical studies showing the effectiveness of orally administered bLf in the prevention of systemic \textit{S. aureus} infections and suggests that future studies investigating lactoferrin’s role in treating \textit{S. aureus} are warranted. IL-10 is a critically important predictor of mortality during infection. Therefore, the observation that bLf lowers serum IL-10 pre-infection and BI increases serum IL-10 post-infection provides evidence that modulation of IL-10 is one potential mechanism by which bLf reduces tissue bacterial abundance in this model of systemic \textit{S. aureus} infection. Furthermore, another indicator of sepsis, NRBC counts, were lower in pigs fed bLf. Although NRBC counts were not affected by the presence of \textit{B. infantis}, exposure to the probiotic increased serum IL-10 levels post-infection potentially indicating that this probiotic should be avoided by neonates at risk of systemic \textit{S. aureus} infection. However, due to its ability to induce IL-10, \textit{B. infantis} may be a useful therapy in already septic neonates. In conclusion, this study suggests that colostrum and mother’s milk,
two liquids with abundant Lf concentrations (47, 48), may protect neonates from *S. aureus* infections and from the complications caused by such infections.

Acknowledgements

We thank Gianna Vella for assistance with conducting the RT-qPCR analyses. We thank Dr. Barbara Pilas in the Roy J. Carver Biotechnology Center Flow Cytometry Core at the University of Illinois for her guidance. The authors’ responsibilities were as follows—EAR: designed the research, conducted the research, analyzed data, performed statistical analyses, wrote the paper; SSC: designed the research, analyzed data and performed statistical analyses, and wrote the paper; JLH: provided technical assistance; MW: provided technical assistance; MJM provided essential reagents and materials as well as technical assistance; SMD: directed the research and has primary responsibility for the final content. All authors have read and approved the final manuscript.
REFERENCES


Tables

**Table 1.** Immune cells in isolated PBMC at 72 and 120h after *S. aureus* infection in piglets fed control formula (CON), control formula with *B. infantis* administration (BI, 3x10⁹ CFU/d) or formula with 4 g/L bLf alone (LF) or with *B. infantis* administration (COMB).

<table>
<thead>
<tr>
<th></th>
<th>72h</th>
<th>120h</th>
<th>% Difference</th>
<th>72h</th>
<th>120h</th>
<th>% Difference</th>
<th>72h</th>
<th>120h</th>
<th>% Difference</th>
</tr>
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<tr>
<td>B-Cells (CD21⁺MHCII⁺)⁹</td>
<td></td>
<td></td>
<td></td>
<td>72h</td>
<td>120h</td>
<td></td>
<td>72h</td>
<td>120h</td>
<td></td>
</tr>
<tr>
<td>CON</td>
<td>4.2±0.8</td>
<td>10.0±2.9</td>
<td>240±59</td>
<td>18.5±5.2</td>
<td>24.9±7.5</td>
<td>192±74</td>
<td>9.6±1.2</td>
<td>10.7±1.2</td>
<td>119±15</td>
</tr>
<tr>
<td>BI</td>
<td>6.1±1.3</td>
<td>11.2±2.6</td>
<td>177±20</td>
<td>20.3±4.2</td>
<td>23.3±5.2</td>
<td>201±71</td>
<td>9.5±0.9</td>
<td>8.3±0.6*</td>
<td>92±9*</td>
</tr>
<tr>
<td>LF</td>
<td>6.0±1.1</td>
<td>8.4±1.8</td>
<td>151±25*</td>
<td>23.5±4.3</td>
<td>18.6±4.6</td>
<td>102±25†</td>
<td>9.2±1.1</td>
<td>10.8±1.2</td>
<td>124±17</td>
</tr>
<tr>
<td>COMB</td>
<td>5.3±1.0</td>
<td>6.6±2.0</td>
<td>112±18*</td>
<td>22.3±4.6</td>
<td>18.7±5.1</td>
<td>104±31†</td>
<td>10.2±1.4</td>
<td>9.0±0.8*</td>
<td>91±9*</td>
</tr>
<tr>
<td>Monocytes(CD14⁺CD163⁺CD172a⁺)⁶</td>
<td></td>
<td></td>
<td></td>
<td>72h</td>
<td>120h</td>
<td></td>
<td>72h</td>
<td>120h</td>
<td></td>
</tr>
<tr>
<td>Memory T-Cells (CD4⁺CD8⁺CD3⁺) ⁷</td>
<td></td>
<td></td>
<td></td>
<td>72h</td>
<td>120h</td>
<td></td>
<td>72h</td>
<td>120h</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: CON, control; BI, *Bifidobacterium infantis*; LF, bovine lactoferrin; COMB, both *Bifidobacterium infantis* and bovine lactoferrin; *S. aureus*, *Staphylococcus aureus* strain S54F9

Data are expressed as Mean ± SEM

⁹ Expressed as a % of total PBMC

⁶ Expressed as a % of CD172⁺ cells

⁷ Expressed as a % of CD3⁺ cells

d Immune cell percentage at 120h divided by the Immune cell percentage at 72h x 100

*Means in a column without a common superscript differ by treatment, P<0.05; †Means in a column without a common superscript showed a trend to differ by treatment, p=0.07
Table 2. Immune-related gene expression in kidney, lung and spleen at 120h after S. aureus infection in piglets fed control formula (CON), control formula with B. infantis administration (BI, 3x10⁹ CFU/d) or formula with 4 g/L bLf alone (LF) or with B. infantis administration (COMB).

<table>
<thead>
<tr>
<th></th>
<th>Kidney</th>
<th></th>
<th></th>
<th>Lung</th>
<th></th>
<th></th>
<th>Spleen</th>
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<tr>
<td></td>
<td>IFNγ</td>
<td>TLR2</td>
<td>IL-10</td>
<td>IFNγ</td>
<td>TLR2</td>
<td>IL-10</td>
<td>IFNγ</td>
<td>TLR2</td>
</tr>
<tr>
<td>CON</td>
<td>1.0±1.0</td>
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<td>1.0±0.3</td>
<td>1.0±0.2</td>
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<td>1.0±0.1</td>
<td>1.0±0.1</td>
<td>1.0±0.1</td>
</tr>
<tr>
<td>BI</td>
<td>1.2±1.1</td>
<td>2.5±0.6*</td>
<td>2.3±1.0</td>
<td>0.9±0.2</td>
<td>1.0±0.3</td>
<td>2.5±2.1*</td>
<td>1.2±0.1</td>
<td>1.0±0.1</td>
</tr>
<tr>
<td>LF</td>
<td>0.6±0.5</td>
<td>1.1±0.1</td>
<td>0.4±0.1*</td>
<td>2.0±0.5*</td>
<td>0.9±0.1</td>
<td>1.6±0.5</td>
<td>1.1±0.3</td>
<td>1.4±0.2</td>
</tr>
<tr>
<td>COMB</td>
<td>1.2±1.3</td>
<td>1.3±0.2</td>
<td>0.7±0.2*</td>
<td>1.5±0.4*</td>
<td>1.2±0.3</td>
<td>1.4±0.6</td>
<td>2.7±0.8*</td>
<td>1.2±0.3</td>
</tr>
</tbody>
</table>

Abbreviations: CON, control; BI, Bifidobacterium infantis; IFNγ, interferon-gamma; IL, Interleukin; LF, bovine lactoferrin; COMB, both Bifidobacterium infantis and bovine lactoferrin; S. aureus, Staphylococcus aureus strain S54F9; TLR, toll-like receptor

A fold-difference was calculated for each measurement by dividing the normalized target values (calculated by dividing the target quantity mean by the RPL-19 quantity mean) by the normalized calibrator values. For samples from the same tissue, values for CON animals were used as the calibrator. *Means in a column without a common superscript differ by treatment, P<0.05
Figure Legends

**Figure 1.** Body weight of piglets fed formula from birth and infected with *S. aureus* on d 7 postpartum. Prior to infection all piglets had similar body weights. The addition of the probiotic *B. infantis* had no effect on body weight, therefore, groups were pooled by bLf supplement: bLf-supplemented (bLf; LF and COMB) and non-bLf supplemented (No bLf; CON and BI) piglets. Following infection, on d10, 11 and 12, bLf-supplemented piglets weighed more than non-bLf supplemented (treatment x time, P<0.0001) piglets. Values are means ± SEM. *P<0.05 between no bLF and bLF. Abbreviations: bLF, bovine lactoferrin.

**Figure 2.** Serum IL-10 concentrations measured prior to *S. aureus* infection and every 12h post-infection. Pre-infection, bLf, but not *B. infantis* significantly affected serum IL-10, therefore groups were pooled by bLf (LF and COMB; n=26) vs. non-bLf (CON and BI; n=23). Prior to infection bLf-supplemented pigs had lower (P=0.01) serum IL-10 concentrations than non-bLf-supplemented pigs (panel a). Following *S. aureus* infection, there was a main effect of time (p=0.03), where animals produced the highest IL-10 concentration at 96 and 108h post-infection (panel b). There was also a main effect of probiotic (P=0.03), but notbLf, therefore values were pooled for probiotic (BI and COMB; n=26) and no probiotic (CON and LF; n=23). Probiotic treated piglets had greater serum IL-10 than non-probiotic treated piglets. Values are means ± SEM, n=11-13 per group. Abbreviations: IL, interleukin; LF, lactoferrin alone; BI, *B. infantis* alone; CON, control; COMB, combined; bLF, bovine lactoferrin.
Figure 3. *S. aureus* counts (CFU/g) in heart, kidney, lung, and spleen 120h after *S. aureus* infection in 12-day-old piglets fed control formula (CON), control formula with *B. infantis* administration (BI, 10⁹ CFU/d) or formula with 4 g/L bLf alone (LF) or with *B. infantis* administration (COMB). There was no effect of *B. infantis*, therefore values were pooled by bLF supplement: bLf-supplemented (LF and COMB; bLf; n=26) and non-bLf-supplemented (CON and BI; No bLf; n=23). No differences were detected at the spleen. Piglets fed diets containing bLf had decreased *S. aureus* counts in the kidney and tended to have decreased CFU/g in the lung and heart. Values are means ± SEM. * P<0.05 and † 0.05>P<0.1 between no bLf and bLf.

Abbreviations: bLf, bovine lactoferrin; LF, lactoferrin alone; BI, *B. infantis* alone; CON, control; COMB, combined; CFU, colony forming units. 
Figure 1

*P<0.05

Body Weight (kg)

Postnatal Day

![Graph showing body weight over postnatal days with a linear trend for both bLf and No bLf groups with statistical significance marked by asterisks (*) at certain points.](image-url)
Figure 2

a) 

Different letter superscripts on each time point, P<0.05

IL-10 pg/ml

<table>
<thead>
<tr>
<th>no bLf</th>
<th>bLf</th>
</tr>
</thead>
<tbody>
<tr>
<td>*P&lt;0.05</td>
<td>*</td>
</tr>
</tbody>
</table>

b) 

Probiotic (B infantis)
No probiotic

IL-10 (pg/ml)

<table>
<thead>
<tr>
<th>Hours Post-Infection</th>
</tr>
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<tbody>
<tr>
<td>0</td>
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SUPPLEMENTAL DATA FOR PUBLICATION

**Supplemental Table 1.** Cocktails of Antibodies used to Detect Immune Cells by Flow Cytometry

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<th>Target Cell Populations</th>
<th>Antibodies in Cocktail (Clone)</th>
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<tr>
<td>T cells/Natural Killer Cells</td>
<td>Anti-CD3 (PPT3)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Anti-CD4 (74-12-4)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Anti-CD8 (76-2-11)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Monocytes/Macrophages</td>
<td>Anti-CD172a (74-22-15)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Anti-CD163 (2A10/11)&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Anti-CD14 (MIL2)&lt;sup&gt;b&lt;/sup&gt;</td>
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<tr>
<td>B cells</td>
<td>Anti-CD21 (BB6-11C9.6)&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
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<td>Anti-SLA class II DR (2E9/13)&lt;sup&gt;b&lt;/sup&gt;</td>
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<sup>a</sup>Southern Biotech (Birmingham, AL, USA)

<sup>b</sup>AbD Serotec, a Bio-Rad Company (Raleigh, NC, USA).

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**Supplemental Table 1.** Cocktails of Antibodies used to Detect Immune Cells by Flow Cytometry

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<tr>
<td></td>
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<td>Anti-CD172a (74-22-15)&lt;sup&gt;a&lt;/sup&gt;</td>
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<td></td>
<td>Anti-CD163 (2A10/11)&lt;sup&gt;b&lt;/sup&gt;</td>
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<td></td>
<td>Anti-SLA class II DR (2E9/13)&lt;sup&gt;b&lt;/sup&gt;</td>
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</tbody>
</table>

<sup>a</sup>Southern Biotech (Birmingham, AL, USA)

<sup>b</sup>AbD Serotec, a Bio-Rad Company (Raleigh, NC, USA).
**Supplemental Table 2.** *B. infantis* in ascending colon contents and feces at 120h after *S. aureus* infection in piglets fed control formula (CON), control formula with *B. infantis* administration (BI, 3x10⁹ CFU/d) or formula with 4 g/L bLf alone (LF) or with *B. infantis* administration (COMB).

<table>
<thead>
<tr>
<th></th>
<th>Occurrence # positive/total # of animals, (%)</th>
<th>Abundance Log₁₀ copies/g</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AC</td>
<td>Feces</td>
</tr>
<tr>
<td>CON</td>
<td>0/12, (0)</td>
<td>1/9, (11)</td>
</tr>
<tr>
<td>LF</td>
<td>1/12, (8)</td>
<td>0/11, (0)</td>
</tr>
<tr>
<td>BI</td>
<td>9/10, (90)*</td>
<td>8/8, (100)*</td>
</tr>
<tr>
<td>COMB</td>
<td>12/13, (92)*</td>
<td>9/9, (100)*</td>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>AC</th>
<th>Feces</th>
</tr>
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<tbody>
<tr>
<td>CON</td>
<td>BLD</td>
<td>BLD</td>
</tr>
<tr>
<td>LF</td>
<td>BLD</td>
<td>BLD</td>
</tr>
<tr>
<td>BI</td>
<td>7.0 ± 1.1*</td>
<td>7.2 ± 1.1*</td>
</tr>
<tr>
<td>COMB</td>
<td>7.5 ± 1.4*</td>
<td>7.4 ± 1.0*</td>
</tr>
</tbody>
</table>

Abbreviations: AC, ascending colon; *B. infantis*, *Bifidobacterium longum* subsp. *infantis* ATCC 15697; BLD, below level of detection; CON, control; BI, *B. infantis*; LF, bovine lactoferrin; COMB, both *B. infantis* and bovine lactoferrin; *S. aureus*, *Staphylococcus aureus* strain S54F9

Data are expressed as Mean ± SD

*Means in a column without a common superscript differ by treatment, P<0.0001
Supplemental Table 3. Whole blood cell populations and percentages determined by CBC/differential analysis in 7-day-old piglets (pre-infection) or 12-day-old piglets (5 days post-infection with *S. aureus*) fed formula with 4 g/l whey (CON), control formula with *B. infantis* administration (BI, 10⁹ CFU/d) or formula with 4 g/l bLf alone (LF) or with *B. infantis* administration (COMB).

<table>
<thead>
<tr>
<th></th>
<th>CON</th>
<th>LF</th>
<th>BI</th>
<th>COMB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hemoglobin, g/dL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-Infection</td>
<td>7.5 ± 0.7</td>
<td>8.2 ± 0.4</td>
<td>7.5 ± 0.5</td>
<td>7.7 ± 0.4</td>
</tr>
<tr>
<td>Post-Infection</td>
<td>6.6 ± 0.3</td>
<td>6.3 ± 0.2</td>
<td>6.2 ± 0.3</td>
<td>6.5 ± 0.2</td>
</tr>
<tr>
<td><strong>NRBC, per 200 WBC</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Pre-Infection</td>
<td>2.0 ± 0.9</td>
<td>2.5 ± 1.1</td>
<td>3.2 ± 0.9</td>
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</tr>
<tr>
<td>Post-Infection</td>
<td>5.4 ± 2.1</td>
<td>3.9 ± 1.5*</td>
<td>9.2 ± 2.6</td>
<td>3.2 ± 1.1*</td>
</tr>
<tr>
<td><strong>WBC Count, per µL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-Infection</td>
<td>8.9 ± 2.1</td>
<td>10.9 ± 1.3</td>
<td>11.1 ± 1.0</td>
<td>9.7 ± 1.9</td>
</tr>
<tr>
<td>Post-Infection</td>
<td>10.0 ± 2.9</td>
<td>10.8 ± 2.0</td>
<td>11.4 ± 2.2</td>
<td>10.8 ± 1.6</td>
</tr>
<tr>
<td><strong>Platelets, x 10³ per µL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-Infection</td>
<td>486 ± 65.6</td>
<td>545 ± 55.9</td>
<td>487 ± 29.4</td>
<td>456 ± 66.8</td>
</tr>
<tr>
<td>Post-Infection</td>
<td>748 ± 71.5</td>
<td>723 ± 46.9</td>
<td>681 ± 90.3</td>
<td>745 ± 46.0</td>
</tr>
<tr>
<td><strong>Seg, %</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-Infection</td>
<td>66.9 ± 4.4</td>
<td>54.2 ± 5.1†</td>
<td>59.4 ± 5.0</td>
<td>51.9 ± 5.9†</td>
</tr>
<tr>
<td>Post-Infection</td>
<td>57.1 ± 5.8</td>
<td>57.3 ± 3.2</td>
<td>60.7 ± 4.7</td>
<td>60.5 ± 4.1</td>
</tr>
<tr>
<td><strong>Band, %, (n detected / total n)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-Infection</td>
<td>0.9 ± 0.9 (1/7)</td>
<td>0.6 ± 0.5 (2/10)</td>
<td>7.0 ± 5.2 (5/10)</td>
<td>1.1 ± 0.7 (3/10)</td>
</tr>
<tr>
<td>Post-Infection</td>
<td>1.4 ± 0.5 (6/11)</td>
<td>0.9 ± 0.3 (7/13)</td>
<td>3.0 ± 1.9 (7/11)</td>
<td>1.0 ± 0.5 (5/13)</td>
</tr>
<tr>
<td><strong>Lymph, %</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre-Infection</td>
<td>30.1 ± 4.4</td>
<td>42.6 ± 5.4*</td>
<td>31.5 ± 4.1</td>
<td>43.2 ± 5.5*</td>
</tr>
<tr>
<td>Post-Infection</td>
<td>37.2 ± 6.1</td>
<td>36.4 ± 3.1</td>
<td>31.6 ± 3.1</td>
<td>34.5 ± 3.6</td>
</tr>
</tbody>
</table>

Data are expressed as Mean ± SEM

*Means in a row without a common superscript differ by treatment, P<0.05; † Means in a row without a common superscript showed a trend to differ by treatment, 0.05≥P<0.10.

Abbreviations: Lymph, lymphocytes; Band, immature neutrophils; Seg, neutrophils; WBC, white blood cells; NRBC, nucleated red blood cells.