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Short communication: Differential immunoglobulin transfer during mastitis challenge by pathogen-specific components

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ABSTRACT

Mastitis induced by *Escherichia coli* is often characterized by severe clinical signs, indicating a more powerful combat of the immune system against the pathogen compared with *Staphylococcus aureus* infections, which are often represented by chronic and subclinical diseases. The aim of this study was to test the major pathogenic component lipopolysaccharide (LPS) from *E. coli* and lipoteichoic acid (LTA) from *Staph. aureus* for their effects on blood-milk barrier integrity and the related transfer of immunoglobulins and lactate from blood into milk. A similar somatic cell count (SCC) increase was achieved by intramammary challenge of 1 quarter of 5 cows with 20 μg of LTA, and 8 cows with 0.2 μg of LPS (maximum log SCC/mL: 7). Milk IgG_1 concentrations increased in LPS- but not in LTA-challenged quarters. Milk IgG_2 concentrations were increased in treated quarters at 3 h after LPS, and 6 h after LTA challenge. Higher maximum levels of IgG_2 were reached in milk of LPS-treated quarters (173 ± 58 μg/mL) than of LTA-challenged quarters (62 ± 13 μg/mL). Immunoglobulin G_1 and IgG_2 levels did not change in control quarters. L-Lactate concentrations in milk increased 4 h after LPS and 5 h after LTA challenge and reached higher maximum levels in LPS- (221 ± 48 mg/L) than in LTA-treated quarters (77 ± 18 mg/L). In conclusion, a mammary inflammation on a quantitatively similar level based on SCC increase achieves a more efficient transfer of blood components such as IgG_2 via the blood-milk barrier if induced by LPS from *E. coli* than by LTA from *Staph. aureus*. This pathogen-specific difference may play an important role in the cure rate of the respective intramammary infection, which is usually lower in *Staph. aureus*- than in *E. coli*-induced mastitis.

Key words: mastitis, blood-milk barrier, lipoteichoic acid, lipopolysaccharide

Short Communication

Intramammary infection with *Escherichia coli* usually causes acute clinical mastitis (Hogan and Smith, 2003), indicating a powerful combat of the immune system against the pathogen. In contrast, intramammary *Staphylococcus aureus* infections are often characterized by chronic and subclinical diseases (Sutra and Poutrel, 1994), and the pathogen seems to be able to prevent significant activity of the immune system. Lipoteichoic acid (**LTA**) and LPS are cell wall components of *Staph. aureus* and *E. coli*, respectively, which are generally accepted as major bacterial components that induce the mammary immune defense. These cell wall components are experimentally used to investigate the mammary immune response (Schmitz et al., 2004; Werner-Misof et al., 2007; Rainard et al., 2008). Choosing dosages to standardize the immune response quantitatively based on a similar SCC increase allowed the study of qualitative differences between these pathogenic components (Wellnitz et al., 2011). Differences in the induction of the mammary immune response by intramammary challenge with LPS and LTA were shown by a different induction of expression of different immune factors (Wellnitz et al., 2011), which most likely plays a role in the development of different mastitis severities.

During inflammation of the mammary gland, a massive leakage of blood constituents into milk occurs due to blood-milk barrier alteration (Burton and Erskine, 2003). Besides SCC, the concentrations of several other parameters increase in milk in response to inflammation of the mammary gland. Not all of these parameters may contribute to the immune response. Immunoglobulin G is the major immunoglobulin in ruminant milk (Butler, 1983). The subclass IgG_1 is the predominant antibody type in milk from healthy quarters because of an active, selective IgG_1 transport across the blood-milk barrier via the neonatal Fc receptor (FcRn) system (Baker et al., 2009). In mastitic milk, IgG_2 becomes the predominant antibody (Caffin and Poutrel, 1988). It is considered to be the main opsonin supporting neutrophil phagocytosis in the bovine mammary gland and, therefore, plays an important role in the combat against mastitis pathogens (Burton and Erskine, 2003).

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L-Lactate (hereafter referred to as lactate) is another blood component that increases in milk during mastitis and is proposed to be used as an early indicator to detect mastitis (Davis et al., 2004). Leukocytes as a source of lactate in milk during an immune response have been considered (Davis et al., 2004). Recently, we described the blood as a major source of milk lactate that leaks into milk as a result of the impairment of the blood-milk barrier during the immune response (Lehmann et al., 2013). The aim of the current study was to investigate the transfer of immunoglobulins and lactate from blood into milk due to a change in the blood-milk barrier integrity after an intramammary challenge with LPS from *E. coli* and LTA from *Staph. aureus* with a comparable SCC increase in milk.

In 13 dairy cows, a similar SCC increase (maximum log SCC/mL: 7) was achieved by intramammary challenge of 1 quarter with 20 μg of LTA (n = 5) from a *Staph. aureus* strain that induced a chronic bovine mastitis, or with 0.2 μg of LPS (n = 8) from *E. coli* that induced acute bovine mastitis, as previously described (Figure 1; Wellnitz et al., 2011). In plasma (jugular vein) and milk samples (~10 mL) taken hourly from challenged and control quarters, IgG_1 and IgG_2 concentrations were analyzed using ELISA (bovine IgG_1/IgG_2 ELISA Quantitation Set; Bethyl Laboratories Inc., LuBioScience GmbH, Lucerne, Switzerland). The procedure was performed according to the manufacturer's protocol. A blocking reagent consisting of fish gelatin [1 mL of fish skin gelatin (G7765; Sigma-Aldrich, Steinheim, Germany) in 20 mL of bidistilled water] was used to avoid matrix effects. Coefficients of variation, calculated using a control sample on each plate, were 10 and 20% within and between assays, respectively. Lactate concentrations were measured using the test kit Lactate PAP (bioMérieux, Marcy l'Étoile, France) with an automated analyzer (Cobas Mira; Roche Diagnostics International AG, Rotkreuz, Switzerland) according to the manufacturer's instructions.

Data are presented as means ± standard error of the mean. Lactate concentrations are presented and statistically evaluated on a logarithmic scale ($\log_{10}$) to ensure normal distribution. Differences within treatment group to time point 0 and between-LPS and -LTA treatments within each time point (hourly) were tested for significance ($P < 0.05$) by ANOVA using PROC MIXED SAS (1999–2001, release 8.02; SAS Institute Inc., Cary, NC). The model included time, treatment, and their interaction as fixed effects, and quarter within cow as repeated subject. A Tukey-Kramer adjustment was used to compensate for multiple comparisons. The significant ($P < 0.001$) Pearson correlation coefficient (SigmaPlot v11; Systat Software Inc., Chicago, IL) between SCC and IgG_1 and IgG_2 in LPS-challenged quarters was 0.42 and 0.33, respectively, and 0.45 and 0.68 between SCC and IgG_1 and IgG_2 in LTA-challenged quarters, respectively.

In blood IgG_1 and IgG_2, concentrations were 16.5 ± 1.1 mg/mL and 35.4 ± 6.8 mg/mL, respectively, and did not change throughout the experiment. Although IgG concentrations in serum are known to be variable due to different factors such as age and lactational stage (Mallard et al., 1983), these are relatively high values compared with those in other studies where concentrations around 10 mg/mL were found for both immunoglobulins (Butler, 1983; Caffin and Poutrel, 1988). Reasons for that remain unclear. The test kits were validated according the manufacturer recommendations. Milk IgG_1 concentrations (Figure 2A) were 68 ± 6, 63 ± 5, and 83 ± 12 μg/mL in control, LPS-, and LTA-challenged quarters before (0 h) challenge, respectively. In LPS-challenged quarters, IgG_1 concentrations increased at 4 and 5 h and from 7 h after challenge until the end of the experiment. The maximum of 105 ± 13 μg/mL was reached 5 h after challenge. In control and LTA-challenged quarters, milk IgG_1 concentrations did not significantly increase.

Milk IgG_2 concentrations (Figure 2 B) were 30 ± 6, 32 ± 8, and 23 ± 8 μg/mL, in control, LPS-, and LTA-challenged quarters before (0 h) challenge, respectively. Milk IgG_2 concentrations increased at 3 h in LPS-challenged quarters, reached the maximum of 173 ± 58 μg/mL at 6 h after challenge, and stayed elevated until the end of the experiment. In LTA-challenged quarters, IgG_2 was increased at 6 h, reached a maximum of 67 ± 9 μg/mL at 8 h, and stayed elevated until 11 h after

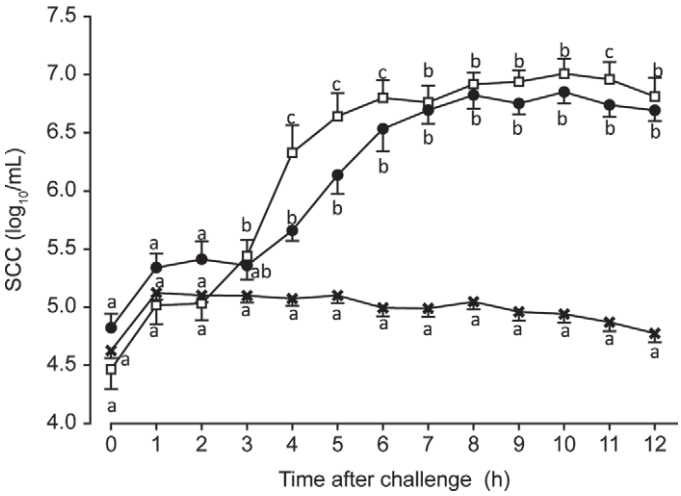

Figure 1. Milk SCC in LPS-challenged quarters (□; n = 8), in lipoteichoic acid (LTA)-challenged quarters (●; n = 5), and in control quarters (x; n = 13). Means without common letters (a–c) are significantly different between groups within a time point ($P < 0.05$). Data are presented as means ± SEM. Reproduced with permission from Wellnitz et al. (2011).

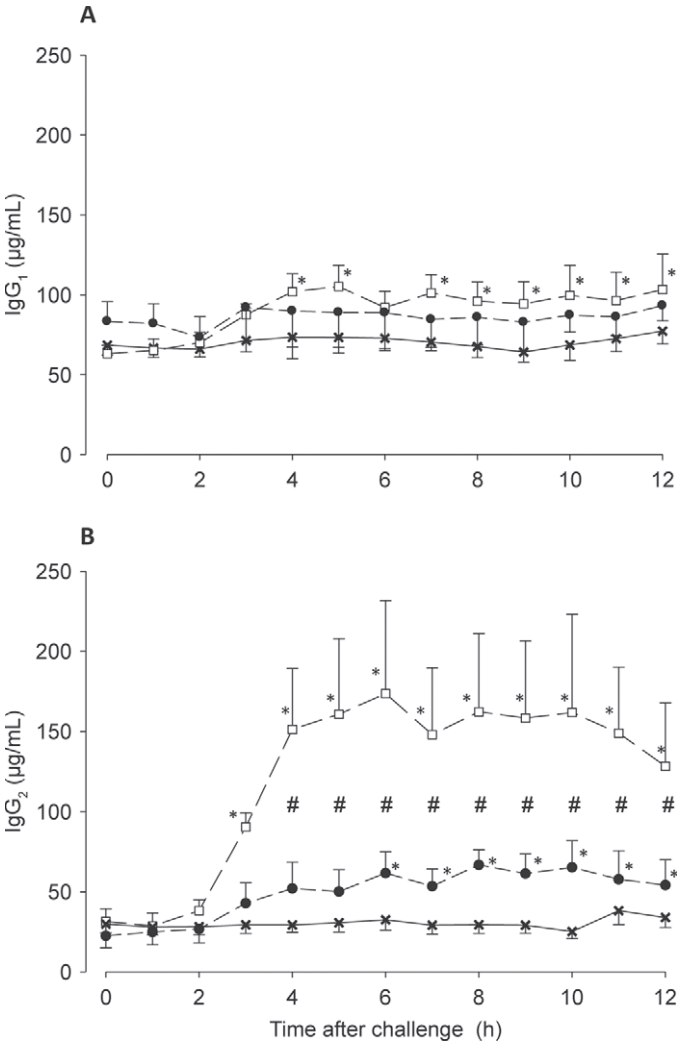

Figure 2. Milk IgG_1 (A) and IgG_2 (B) concentrations in LPS-challenged quarters (□; n = 8), in lipoteichoic acid (LTA)-challenged quarters (●; n = 5), and in control quarters (x; n = 13). * indicates the first and subsequent time points with a significant ($P < 0.05$) difference compared with time 0; # indicates significant ($P < 0.05$) differences between LPS- and LTA-challenged quarters within a time point. Data are presented as means ± SEM.

challenge. In control quarters, milk IgG_2 concentrations did not significantly increase.

The present study clearly shows that LPS of *E. coli* obviously opens the blood-milk barrier to a greater extent than LTA from *Staph. aureus*, despite a similar SCC increase in response to both treatments. This mechanism could be involved in the mainly chronic development of mastitis by *Staph. aureus* because an insufficient amount of antibodies and other immune factors from blood are transferred into milk due to a reduced opening of the blood-milk barrier induced by these bacteria.

Concentrations of IgG_2 in milk raised to a greater extent (5 fold after LPS challenge) than IgG_1 (3 fold after LPS challenge) although these molecules have comparable molecular weights of approximately 160 kDa (Butler, 1983) and should be able to pass the blood-milk barrier in a comparable way. The IgG_1:IgG_2 ratio in milk at 5 h after LPS challenge was 1:1.5, whereas the ratio in blood was 1:2.1. This was mainly due to the specific transport of IgG_1 (Mayer et al., 2005) that was also responsible for a 2.5:1 ratio in milk before LPS challenge. In addition, specific transport of IgG_2 has been discussed (Newby and Bourne, 1977) and binding of IgG_2 to mammary epithelial cells has been reported (Sasaki et al., 1977). However, during lactation of the healthy mammary gland, passive transfer of IgG_2 from the blood is assumed (Guidry et al., 1980).

As IgG_2 plays a particular role in the mammary immune defense, the availability of antibodies in the milk can be crucial for mastitis defense, specifically if antibodies against the invading mastitis pathogens are available in the blood. Although IgG_2 also enter the milk bound to PMNL (Butler, 1983), the majority of milk IgG_2 that appear in milk during mammary inflammation leak into mammary gland from the blood (Burton and Erskine, 2003). That differences in the IgG_2 content in the milk during mastitis can depend on the pathogen has been reported (Caffin and Poutrel, 1988).

Lactate is another blood component whose appearance in milk was tested with the intramammary LPS or LTA challenge. The blood lactate concentration was 54.9 ± 1.2 mg/L before LPS challenge and did not change throughout the experiment. Lactate concentrations in milk (Figure 3) were increased at 4 h after challenge in LPS-treated quarters and 5 h after challenge in LTA-treated quarters and both stayed elevated until the end of the experiment. At 4 h after challenge to 11 h after challenge, the lactate concentrations in milk were higher in LPS- than in LTA-treated quarters. This greater increase in lactate concentration in milk of quarters challenged with LPS compared with quarters challenged with LTA also shows a different characteristic in the change of blood-milk barrier permeability in response to *E. coli* compared with *Staph. aureus* endotoxin. The small molecular size (90 Da) of lactate facilitates transfer from blood into milk. However, milk concentration of lactate increased up to 4.0-fold higher levels of those in blood (220.7 ± 48.1 mg/L) at 8 h after LPS challenge and to 1.4 fold (76.8 ± 18.3 mg/L) 10 h after LTA challenge. This effect was seen before (Lehmann et al., 2013). This effect was suggested to be due to additional lactate production and release during anaerobic metabolism by milk and epithelial cells in the gland (Silanikove et al., 2011) or to be an effect of an

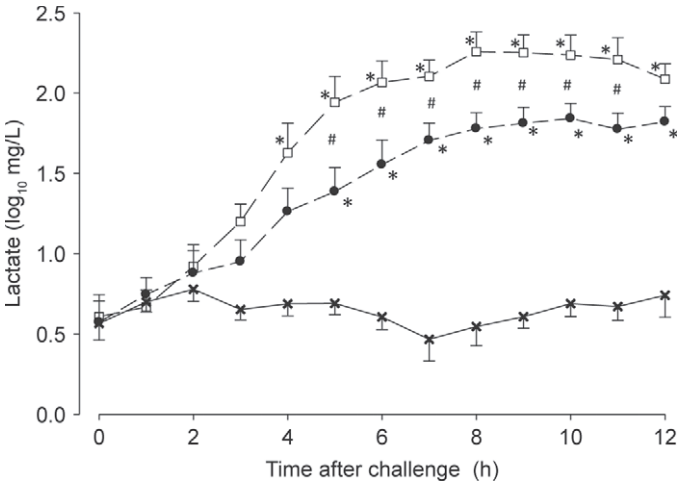

Figure 3. Milk lactate concentrations in LPS-challenged quarters (□; n = 8), in lipoteichoic acid (LTA)-challenged quarters (●; n = 5), and in control quarters (x; n = 13). * indicates the first and subsequent time point with a significant ($P < 0.05$) difference compared with time 0; # indicates significant ($P < 0.05$) differences between LPS- and LTA-challenged quarters within a time point. Data are presented as means ± SEM.

additional transporter system for lactate, which could be via aquaporins, as aquaporins transport lactate (Conde et al., 2010) and aquaporins are present in the bovine mammary gland (Mobasheri et al., 2011).

Mammary challenge equalized for SCC increases produces a greater and differential permeability of the blood-milk barrier for immunoglobulins when induced by LPS from *E. coli* compared with LTA from *Staph. aureus*. Thus, more efficient transfer of blood components such as IgG_2 is achieved with *E. coli*, which predominantly induces acute and severe mastitis compared with LTA from *Staph. aureus*, which is responsible for more chronic and subclinical mastitis. This effect could have an important influence on the cure rate of the respective IMI, which is usually lower in *Staph. aureus*- than in *E. coli*-induced mastitis, specifically if antibodies against the mastitis pathogen are present in the blood (e.g., after vaccination).

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