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Immune Activation and Suppression by Group B Streptococcus in a Murine Model of Urinary Tract Infection

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Group B streptococcus (GBS) is the leading cause of serious infections in newborns, the elderly, and immunocompromised populations. GBS also causes infections of the skin, lungs, and urinary tract and is increasingly associated with invasive infections in adult populations such as pregnant women, diabetics, and the elderly (11, 16, 48, 65). GBS colonizes the gastrointestinal and vaginal mucosa of approximately 30% of individuals tested at a given time and nearly 2/3 of those tested at multiple intervals over a year (35). While GBS colonization occurs asymptomatically, localized infections of the skin, lungs, and urinary tract are associated with progression to serious systemic infections in individuals with a compromised or underdeveloped immune system (4, 16, 48, 65). For example, vaginal colonization in late pregnancy is associated with vertical transmission of GBS in utero due to ascending amniotic infection or by aspiration of contaminated vaginal fluids during delivery. Pneumonia, sepsis, and meningitis are potential complications of GBS transmission to the neonate, reflecting an array of bacterial virulence factors that act to impede phagocytic clearance, resulting in host tissue injury (10). Much of what is known about GBS virulence has been defined in animal models of systemic infection (18, 20, 23, 25, 28, 46, 47). GBS has also been described in animal models of localized colonization and infection, including vaginal (7, 8), pulmonary (15, 19, 22), mammary (52), and orogastric (27) infection models. GBS can also cause cystitis and pyelonephritis (54, 55), but the urinary tract is less well characterized as a site of GBS-host interactions.

Asymptomatic bacteriuria and urinary tract infection (UTI) caused by GBS are common among pregnant, elderly, and otherwise immunocompromised individuals, groups with a higher risk of ascending pyelonephritis that can progress to bacteremia (11, 16, 53, 55). It has been estimated that up to 7% of pregnant women have significant titers of GBS in their urine (36). While typically asymptomatic, GBS bacteriuria in pregnancy is an independent risk factor for maternal pyelonephritis and chorioamnionitis as well as neonatal GBS disease (1, 36, 41, 42). Other studies of elderly populations with UTIs show an involvement of GBS in as many as 39% of nursing home residents over 70 years of age (4). This result stands in striking contrast to the proportion of UTIs associated with GBS in younger populations, estimated at 1 to 2% (14). Despite the abundant molecular epidemiological data regarding GBS, little is known about GBS UTI pathogenesis. This dearth of understanding contrasts dramatically to our extensive knowledge of disease processes involving the more common etiologic agent of UTI, uropathogenic Enterococcus coli (UPEC), which successfully utilizes multiple immune evasion strategies to persist within the urinary tract (45, 49, 61, 62).

During systemic infection, GBS employs a number of strategies to avoid recognition and clearance by the host immune system. Capsular polysaccharide is one of the best-characterized GBS virulence factors. GBS capsule is critical for systemic disease progression in animal models (60). More specifically,
the outermost sialic acid residues of the capsule polymer, which are identical to host surface moieties, limit complement deposition, prevent phagocytosis, and suppress neutrophil oxidase burst and granule protease release (2, 6, 12, 34, 50). Recent studies demonstrated that GBS surface sialic acids interact with host sialic acid binding immunoglobulin-like lectins (Siglecs), a family of surface receptors that are expressed on immune cells (5). Interactions between GBS sialic acids and human polymorphonuclear leukocyte (PMN) Siglec-9 lead to reduced PMN bactericidal functions and limit GBS killing, whereas modification of GBS sialic acids with high levels of O-acetylation impairs Siglec-9 binding and neutrophil suppression (6, 57, 58).

Another important virulence factor of GBS is the β-hemolysin/cytolysin, a pore-forming toxin responsible for the characteristic beta-hemolytic phenotype of GBS on blood agar plates (13). Expression of β-hemolysin/cytolysin is correlated with disease severity in murine models of intranasal and intravenous administration, consistent with its ability to produce injury in both red blood cells and pulmonary epithelial and endothelial cells (33, 43, 51). Studies also demonstrate a role of β-hemolysin/cytolysin during adherence of lung epithelium and induction of neutrophil chemoattractant cytokine interleukin-8 (IL-8) (9).

In this study, we sought to develop a robust murine model to more fully characterize infection dynamics and host response to GBS in the urinary tract. Here we elucidate several fundamental aspects of GBS-induced soluble and cellular inflammation in the murine bladder and kidney and define GBS capsule sialic acid (but not β-hemolysin/cytolysin) to be an important determinant for host association in the urinary tract.

MATERIALS AND METHODS

Ethics statement. All animal studies were performed in accordance with approvals from the Committee for Animal Studies at Washington University School of Medicine.

Bacterial strains and growth conditions. Uropathogenic E. coli strain UTI89 (37) or UTI89::HKGFpkan’ (63) was inoculated from single colonies grown on LB agar into Luria broth containing kanamycin at 25 µg/ml where appropriate and grown statically overnight (18 to 24 h) at 37°C. Similarly, the well-characterized Streptococcus agalactiae strain COH1 or clinical strains provided by Walt Stamm (University of Washington) and Thomas Hooten (University of Florida) were inoculated from single colonies grown on Todd-Hewitt (TH) agar into TH broth (Difco) with antibiotics where appropriate and grown statically overnight (18 to 24 h) at 37°C. For GBS, bacteria were diluted and grown to log phase (optical density at 600 nm, 0.4) just prior to infection. Evaluation of GBS virulence factors important for urinary tract pathogenesis was carried out using previously published strains. Genetic manipulation of neuA, a bifunctional O-acetylerase/sialic acid synthetase, was utilized for isogenic variation of capsular structure as previously described (29, 30). Specifically, GBS strains lacking a chromosomal copy of neuA (ΔneuAp) accumulate intracellular O-acetylated sialic acids and do not express capsule sialic acids (asialo). GBS strains that overexpress wild-type NeuA (ΔneuApneuA or COH1 wild type/ΔneuAp) express indistinguishable levels of sialic acids with minimal O-acetylation (GBS-loOAc), whereas a point mutation in NeuA leads to hyper-O-acetylation of sialic acids (ΔneuApneuA4890; GBS-hiOAc). These strains have been extensively characterized (29, 30, 57, 58). The acapsular GBS strain was previously described and compared in our experiments to the parent wild-type strain (64). The cytE mutant was constructed in the highly hemolytic NCTC 10/84 strain background and was kindly provided by Victor Nizet (9).

Murine infections. Bacterial cultures, grown as described above, were collected by centrifugation and resuspended in phosphate-buffered saline (PBS). Female wild-type mice 7 to 8 weeks of age were obtained from Harlan (C3H/HeN). Mice were anesthetized by inhalation of 3% isoflurane and inoculated transurethrally with ~1 × 10^7 CFU in 50 µl (16, 29). At indicated time points, mice were euthanized and bladders and kidneys were aseptically removed. The number of bacteria present in the tissues was determined by homogenization of bladders or kidney pairs in PBS and plating of serial dilutions on TH agar (for GBS) or LB agar (for UPEC) supplemented with antibiotics when appropriate. For competition experiments, GBS mutants were coinoculated at equal doses of 10^7 CFU per strain, followed by organ CFU enumeration on TH agar supplemented with appropriate antibiotics. Statistical analyses were performed using the Mann-Whitney U test with Prism software (version 5.00 for Windows; GraphPad Software). Recovered titers of zero were set to the limit of detection of the assay.

RESULTS

The murine model of GBS UTI. GBS serotypes Ia, III, and V are most prevalent among human UTIs caused by GBS (55). Among these, serotype III appears to have a unique predilection for causing symptomatic compared to asymptomatic UTI (55). Here we establish a urinary tract infection model using the well-studied serotype III strain COH1. After transurethral inoculation of young (7- to 8-week-old) female C3H/HeN mice with a single instillation of GBS strain COH1, we observed low-level bladder GBS colonization in organ homogenates that peaked at 3 h postinfection (hpi) and gradually diminished thereafter (Fig. 1A). The numbers of CFU recovered from...
Kidney homogenates were highest at 24 hpi and were significantly higher than the numbers of CFU recovered from the bladders at 1, 3, and 7 days postinfection (dpi) (Fig. 1B). As a comparison, inoculation of mice with UPEC strain UTI89 resulted in significantly higher bladder titers than inoculation of mice with GBS, while GBS and UPEC colonized the kidney equally at 24 hpi (Fig. 1C). A minimally passaged clinical isolate of GBS, isolated from a human UTI, also demonstrated significant kidney tropism (data not shown), similar to other major Gram-positive uropathogens, *Staphylococcus saprophyticus* and *Enterococcus faecalis* (24, 26).

**Innate immune response to GBS UTI.** To assess the host factors that contribute to GBS UTI, the profiles of 23 different cytokines and chemokines were examined in bladder homogenates of mice at 24 hpi. GBS infection resulted in induction of IL-1α, macrophage inflammatory protein-1α (MIP-1α), MIP-1β, IL-9, and IL-10 compared to PBS mock-infected bladders (Fig. 2A). At 24 hpi, the serum cytokines induced in the same animals during GBS infection included KC, RANTES, and IL-12p40 (Fig. 2B). In addition, IL-1α and MIP-1β were induced 15- and 3-fold *(P < 0.10)*, respectively. These observations together represent a host response to GBS UTI consisting of cytokines and chemokines that are primarily secreted by monocytes and/or epithelial cells and that serve to attract and activate PMNs.

Next, organ histology was examined at 3 h and 24 h after infection. H&E staining of GBS-infected kidneys, which have higher numbers of bacterial CFU than the bladder (Fig. 1), displays large collections of immune cells in the renal pelvis and at focal sites at 3 and 24 hpi (Fig. 3A to C), with both organs containing bacteria and immune cells with morphology indicative of PMNs, monocytes, and lymphocytes (Fig. 3E to G). No inflammation was observed in PBS-treated kidneys (Fig. 3D). In contrast, GBS-infected bladders revealed minimal visible inflammatory infiltrate at the time points examined (Fig. 3H to J), similar to PBS-treated bladders (Fig. 3K). Given the composition of bladder cytokines, it is likely that PMNs are also present in the bladder but are not detectable by gross histology. Similarly, low and dispersed bacterial titers in the bladder at this time point were difficult to detect by H&E staining, even though they were quantifiable by CFU analysis.

**GBS glycan mimicry limits murine PMN oxidative burst and bactericidal activity.** We have previously characterized a naturally occurring GBS capsule modification (sialic acid O-acetylation), which is expressed at low to moderate levels in all tested serotypes (30, 58). Site-specific mutation of a GBS glycan on C3H/HeN female mice (7 to 8 weeks old) were transurethrally inoculated with 10⁷ CFU GBS or UPEC in 50 µl, and the CFU in the bladder (A) or kidney (B) was enumerated at the indicated time points. The numbers of GBS or UPEC CFU were directly compared at 24 hpi (C). Results represent a compilation of 1 to 2 experiments (A and B) and a compilation of 4 experiments (C), using at least 5 mice per time point. The limit of detection of the assay is indicated by a dashed line. Statistical significance was determined by a two-tailed Mann-Whitney U test: *, *(P < 0.05); **, *(P < 0.01); n.s., not significant. Statistical significance shown in panel B denotes comparison to the numbers of bladder CFU at the same time point.
O-acetylesterase has facilitated genetic control of O-acetylation levels (here referred to as GBS-hiOAc [80% of total surface sialic acids modified] and GBS-loOAc [~2% of total surface sialic acids modified]) (29). Previous studies have shown that O-acetylation does not impact GBS complement evasion but does impede sialic acid–Siglec-9 engagement and thus attenuates bacterial evasion of human neutrophils (57, 58). Murine neutrophils express a homolog of human Siglec-9 called Siglec-E. However, it is not known whether GBS can evade murine neutrophils by sialic acid-dependent processes.

Therefore, we investigated the hypothesis that the GBS sialic acid capsule facilitates the evasion of murine neutrophil killing in early stages of UTI as part of a mechanism to persist in the murine urinary tract. We hypothesized that GBS-loOAc would better mimic the host sialic acid structure (Fig. 4A) and promote PMN suppression and bacterial survival than GBS-hiOAc. To test this hypothesis in vitro, GBS-loOAc and GBS-hiOAc were incubated with murine peritoneal PMNs for 30 min, and the surviving bacteria were enumerated. GBS-loOAc survived significantly better than GBS-hiOAc in four independent experiments (Fig. 4B). As a control, we show that bacteria lacking capsular sialic acids are also killed significantly better by murine PMNs than GBS-loOAc. In contrast, GBS-hiOAc and GBS-asialo were killed similarly by murine PMNs. Consistent with previous studies with peripheral human leukocytes (59), we show that GBS lacking capsule is killed significantly more readily by murine PMNs than its isogenic wild-type parent strain (data not shown). In addition, we measured the oxidative burst of isolated murine PMNs using kinetic luminol detection of the reactive oxygen species released following pathogen exposure. This analysis revealed that PMNs were significantly more activated in the presence of GBS-hiOAc than in the presence of GBS-loOAc (Fig. 4C and D).

FIG. 3. Robust inflammation in the kidney of GBS-infected animals. Hematoxylin-eosin staining of GBS-infected C3H/HeN murine kidneys (A to G) or bladders (H to K) at 3 hpi (A B, E, F, and H) or 24 hpi (C, G, I, and J). PBS mock-infected kidney (D) and bladder (K) at 24 hpi are shown. Representative images are shown at magnifications of ×10 (A to D, K), ×40 (I and J), ×60 (F to H), and ×100 (E). (E to G) Boxed areas from panels A to C, respectively.
GBS capsule sialic acids suppress PMN proinflammatory cytokine induction. We hypothesized that the observed suppression of bactericidal activity by GBS sialic acids may also be accompanied by a suppression of PMN cytokine responses. Consistent with the \textit{in vitro} data showing suppression of PMNs in the presence of GBS-loOAc compared to the level of PMN induction in the presence of GBS-hiOAc (Fig. 4B and D), we observed reduced PMN production of the proinflammatory cytokines IL-1\(\alpha\), tumor necrosis factor alpha (TNF-\(\alpha\)), IL-1\(\beta\), MIP-1\(\alpha\), and KC upon exposure to GBS-loOAc compared to that upon exposure to GBS-hiOAc (Fig. 5). After short-term exposures of PMNs to live bacteria (60 min), GBS-loOAc induced significantly lower levels of IL-1\(\alpha\) and TNF-\(\alpha\) than GBS-hiOAc (Fig. 5A). To better define the impact of GBS sialic acid structure on cytokine levels at later time points, heat-killed GBS was used to stimulate PMNs for 180 min, followed by cytokine measurement (Fig. 5B). Heat-killed bacteria were used to eliminate the confounding effects of differential bacterial survival in the presence of PMNs over time. At the later time point, there were significantly reduced levels of IL-1\(\beta\), MIP-1\(\alpha\), and KC induced by GBS-loOAc compared to those induced by GBS-hiOAc. Thus, \textit{in vitro} experiments demonstrate that GBS is able to suppress murine PMN cytokine responses in a sialic acid-dependent fashion that is impaired by sialic acid O-acetylation.

GBS capsule sialic acids impair bladder virulence and are disarmed by O-acetylation. To directly test whether GBS capsular sialic acids contribute to pathogenesis in the urinary tract, we infected mice with GBS-loOAc and GBS-hiOAc and compared the disease outcome to that in mice infected with GBS expressing no sialic acid residues. Consistent with the \textit{in vitro} data, strains expressing high levels of O-acetylation or lacking sialic acid residues displayed significantly reduced numbers of CFU in the murine bladder at 24 hpi compared to GBS-hiOAc (Fig. 6A). In fact, GBS with high levels of sialic acid O-acetylation did no better in the bladder than GBS lacking sialic acids. Interestingly, very few (2/21) of the animals infected with GBS-loOAc had completely cleared the infection by 24 h, whereas over one-third (9/26) of the animals infected with GBS-hiOAc had sterile bladders at this time point (Fig. 6A). The GBS sialic acid structure did not appear to alter the outcome of infection in the kidney at the 24-h time point (Fig. 6B). This was somewhat surprising, since both PMNs and monocytic cellular infiltrates were seen in the kidney in response to GBS infection (Fig. 3). Thus, further evaluation of GBS titers at 72 hpi were performed and showed a moderate but statistically significant reduction in GBS-hiOAc titers in the kidney compared to the GBS-loOAc strain titers (data not shown). More strikingly, competition studies showed a rapid and complete exclusion of GBS-hiOAc in the presence of GBS-loOAc in both the bladder and kidney in all animals coinfected with both strains (Fig. 6C). In contrast to the apparent role of sialic acid structure in GBS UTI pathogenesis, investigation of the GBS \(\beta\)-hemolysin/cytolysin encoded by \textit{cylE}, which is important for virulence in virtually all other animal infection models (9, 19, 31, 44), showed no significant differences in acute bladder or kidney UTI compared to the isogenic wild-type strain (data not shown).

DISCUSSION

Urinary tract infections are among the most common bacterial infections in humans. UTI ranges from asymptomatic bacteria in the urine to a painful infection of the bladder (cystitis) or kidney (pyelonephritis) and can also progress to infection of the blood in susceptible individuals. UPEC is the most common cause of UTIs. However, both the incidence of UTI and the profile of etiologic agents responsible for UTIs differ across the age spectrum. For example, whereas GBS
FIG. 5. GBS capsular sialic acid modification alters PMN cytokine production. Murine PMN culture supernatants were collected after 60 min of incubation with live GBS or PBS (A) or 180 min of incubation with heat-killed GBS or PBS (B) and assayed for cytokine production. Data are represented as fold change compared to the results for PBS-treated PMN at the same time point (n = 3). Significant differences between GBS-hiOAc or GBS-loOAc infection were measured by the unpaired t test: *, P < 0.05; **, P < 0.01. Each panel and statistical evaluation includes data from at least 3 independent experiments.

FIG. 6. GBS capsular sialic acid O-acetylation limits virulence in the bladder. C3H/HeN mice were infected with isogenic GBS bearing surface structural alterations of the capsular polysaccharide. The numbers of CFU in bladder (A) and kidney (B) were enumerated at 24 hpi (n = 3 to 5 experiments with at least 5 mice per group). The limit of detection of the assay is indicated by a dashed line, and statistical analysis was performed as described in the legend to Fig. 1. (C) Competition experiments were performed by coinoculation of $10^7$ each of GBS-hiOAC and GBS-loOAc containing different antibiotic resistance markers, followed by bacterial enumeration at 24 hpi.

causes only ~1% of UTIs in young healthy individuals, it causes nearly 40% of infections in elderly populations, where it is also strongly associated with both pyelonephritis and invasive infections (38, 53, 55). GBS cystitis and asymptomatic bacteriuria are also more prevalent during pregnancy and are independent risk factors for pyelonephritis, chorioamnionitis, and preterm labor (56). The basis for such a diverse spectrum of disease states is not well understood.

A robust animal model is required to elucidate host and bacterial factors that contribute to GBS asymptomatic urinary tract colonization and UTI pathogenesis. It is known that different mouse backgrounds are differentially susceptible to UTIs with UPEC (21). For example, the C57BL/6 mouse strain displays rapid uroepithelial exfoliation and is susceptible to quiescent intracellular reservoir formation in response to UPEC infection (39, 40). Alternatively, the C3H/HeN mouse strain is susceptible to both acute and chronic active cystitis in response to UPEC inoculation (17). A recent study described a murine model of GBS UTI using an inoculum of $10^9$ CFU instilled transurethrally into C57BL/6 mice (54). In the current study, we use a much lower dose of $10^7$ CFU GBS in the mouse strain C3H/HeN.

Using this model, we have found that GBS is significantly better able to cause disease in the kidney than in the bladder, a feature shared with the Gram-positive uropathogens *E. faecalis* and *S. saprophyticus* (24, 26). The cytokine profile observed in GBS UTIs is unique compared to that observed in UTIs caused by other uropathogens. However, not surprisingly, the overall host cytokine response to GBS is more similar to responses seen in catheter-associated *Enterococcus faecalis* UTI than UPEC UTI (17, 19). GBS infection of the murine kidney results in an immune response characterized by innate cellular recruitment. The proinflammatory response in the urinary bladder included IL-1β, which is produced by epithelial cells as well as macrophages and other leukocytes, and is consistent with an earlier study showing strong induction of this cytokine upon GBS urinary tract infection (54). The soluble response to GBS infection in the bladder also included the monocyte/macrophage chemokines MIP-1α and MIP-1β. The significant induction of macrophage-associated cytokines and chemokines produced in response to GBS infection in the absence of a significant macrophage infiltrate into the infected bladder suggests that resident macrophages may be activated during infection. The presence of PMN migration and maturation signals such as IL-1α and MIP1-α/β, along with KC, in the serum is also consistent with a role for a PMN response to the GBS-infected bladder.

Taken together, the data suggest that during UTI, GBS triggers proinflammatory signals while simultaneously suppressing immune responses. Past *in vitro* studies have shown that serotype III GBS can directly dampen the host bactericidal response by engaging Siglecs on human PMNs via capsular sialic acids (6). The experiments presented here show that the sialic acid-containing capsular polysaccharide of serotype III GBS can also modulate the function of murine PMNs to dampen bactericidal capacity and cytokine responses and
enhance bacterial virulence during a localized murine urinary tract infection. Our finding of increased IL-10 levels in a GBS-infected bladder is consistent with earlier findings showing GBS-specific upregulation of IL-10 in other infection models (6, 32). This is potentially relevant to GBS-dependent immune suppression since IL-10 has been described to be a cytokine able to control the degree and duration of an inflammatory response. It is able to simultaneously dampen inflammation by blocking the expression of proinflammatory cytokines while also promoting the expression of anti-inflammatory molecules (3). Interestingly, GBS is the first example of a uropathogen that stimulates production of IL-10 in the urinary tract. Taken together, these observations suggest that GBS acts through multiple mechanisms to suppress immune processes during urinary tract infection.

While GBS causes both cystitis and pyelonephritis in humans, it is difficult to know the nidus of infection on the basis of clinical symptoms alone. For example, it cannot be ruled out that the presentation of GBS in the kidney might present as cystitis or that the kidney itself could be a reservoir of asymptomatic GBS colonization. Here we demonstrate a tropism of GBS for the murine kidney, a finding that may be relevant to human UTI. Taken together, the apparently mild inflammatory response initiated by GBS in the bladder, tropism of GBS for the kidney, and sialic acid-mediated GBS immune evasion in the bladder show that GBS has multiple overlapping strategies for persistence in the urinary tract.

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