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Enterococcus faecalis Tropism for the Kidneys in the Urinary Tract of C57BL/6J Mice

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Enterococcus faecalis **is a gram-positive bacterium that can cause a variety of nosocomial infections of which urinary tract infections are the most common. These infections can be exceptionally difficult to treat because of drug resistance of many *E. faecalis* isolates. Despite their troublesome nature, little is known about the host or bacterial factors necessary for *E. faecalis* to cause disease in the urinary tract. Using a mouse model of urinary tract infection, we have shown that *E. faecalis* is capable of persisting in the kidneys of mice for at least 2 weeks. In contrast, bacterial titers from the bladders of the same mice were inconsistent and tended to be much lower than those recovered from the kidney. This preference for the kidney over the bladder is also observed in other clinical *E. faecalis* strains. Histologic examination of bladder and kidney tissues demonstrated that *E. faecalis* induced an inflammatory response in the kidney but not in the bladder. This inflammatory response was TLR2 independent and did not induce inflammatory markers typically associated with uropathogenic *Escherichia coli*. Using a competition assay, we demonstrated that a pyelonephritis clinical isolate had a growth advantage over a laboratory strain of *E. faecalis* in the kidneys but not in the bladders of mice. Taken together, these results demonstrate that *E. faecalis* has tropism for the kidneys in the urinary tracts of mice and that this system can be used to study factors involved in the pathogenesis of urinary tract infections.**

Enterococcus faecalis, while normally a gut commensal, is a frequent cause of many serious human infections, including urinary tract infections, endocarditis, bacteremia, and wound infections. Among the diseases that *E. faecalis* causes, urinary tract infections are the most common, responsible for approximately 110,000 cases yearly, many of which are nosocomial. Infections with *E. faecalis* can be especially troublesome to treat because of their frequent resistance to multiple antibiotics, including vancomycin, a drug of last resort for many gram-positive infections (for a review, see reference 8).

Both rat and mouse model systems have been used to study factors involved in the pathogenesis of *E. faecalis* in the urinary tract. Studies by Guze and colleagues showed that *E. faecalis* has a growth advantage over other enterococcal species in rat kidneys in a hematogenous inoculation pyelonephritis model (18). Another model system was used to show that pyelonephritis caused by *Pseudomonas aeruginosa* was aggravated by coinfection with *E. faecalis*, as determined by histological changes in the kidney (30). In this model, ligation of the urethra was used to induce retrograde reflux of bacteria into the kidney, increasing the susceptibility of the mouse to infection. In a bladder catheterization model of urinary tract infection, the Esp (enterococcal surface protein) adhesin was found to increase persistence in the urinary bladder of mice, although no histological changes were observed (26). Another study was unable to demonstrate a critical function for aggregation substance, a well-characterized enterococcal adhesin, in a murine model of cystitis (12). Thus, a robust murine cystitis model of *E. faecalis* infection has yet to be established, most likely due to complicating host and bacterial factors reflecting the adaptations enterococcus has evolved to coexist with its host. In order to more effectively devise strategies and therapies to prevent and treat enterococcal urinary tract infections, an infection model that can give a sensitive readout of virulence factors must be developed.

In contrast, many of the host-pathogen interactions critical for bladder infections caused by uropathogenic *Escherichia coli*, the most common etiologic agent of urinary tract infections, have been well-defined in murine models. Uropathogenic *E. coli* initially interacts with bladder epithelium through the expression of type 1 pili, which mediate adhesion and invasion into the uroplakin-expressing umbrella cells on the surface of the bladder (19). The invasion of *E. coli* into the urinary epithelium results in expression of a variety of cytokines, induction of apoptosis in infected cells, and a massive neutrophil inflammatory response. This response is mediated primarily by Toll-like receptor 4, which has been demonstrated to respond to lipopolysaccharide (22, 23). The interaction of *E. coli* with the mouse kidney epithelium during pyelonephritis is less well characterized, but the importance of P pili is well established as an initial mediator of adherence in other animal models (21). Similar to bladder infections, acute *E. coli*–mediated pyelonephritis in mice is characterized by a strong neutrophil immune response (4).

In this study, we describe the tropism of *E. faecalis* for the kidneys in C57BL/6J mice. The consequences of this tropism were investigated by characterizing the host response to *E.*

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TABLE 1. Strains used in this study

Strain	Species	Resistance(s)	Source	Reference(s)
NU14	*E. coli*	Str^r	Cystitis isolate	7, 16
OG1X	*E. faecalis*	Str^r, Tet^s	Gelatinase-negative, plasmid-free strain derived from an oral isolate by nitrosoguanidine mutagenesis	9, 10
0852	*E. faecalis*	Tet^r	Urinary tract isolate, not otherwise specified	This study
B1223	*E. faecalis*	Tet^r	Cystitis isolate	This study
B1384	*E. faecalis*		Cystitis isolate	This study
P1503	*E. faecalis*	Tet^r	Pyelonephritis isolate	This study
BP78	*E. faecalis*	Tet^r, Str^s	Pyelonephritis isolate	This study
BP250	*E. faecalis*	Tet^r	Pyelonephritis isolate	This study

faecalis and contrasting these differences to the response induced by uropathogenic *E. coli*.

MATERIALS AND METHODS

Strains and growth conditions. A summary of all the strains used in this study, their origins, and relevant drug resistances are shown in Table 1. For infection of mice, *E. faecalis* strains were grown statically overnight (typically 12 to 15 h) at 37°C in brain heart infusion (BHI) medium (Difco) without antibiotics. Clinical strains other than 0852 were contributed by Thomas Hooten and Walter Stamm (University of Washington) and categorized as either cystitis or pyelonephritis strains using clinical criteria.

Animals. Female wild-type C57BL/6 mice were obtained from Jackson Laboratories and C57BL/6 $TLR2^{-/-}$ mice were a gift of S. Akira (29). $TLR2^{-/-}$ mice were 36 to 48 weeks in age at the time of inoculation. Wild-type 12-week-old and 52-week-old mice were used to control for the various ages of the $TLR2^{-/-}$ mice. These experiments demonstrated that there was no substantial difference in the recoveries of *E. faecalis* due to the ages of the mice. In all other experiments, mice were 8 to 12 weeks of age.

Inoculation and CFU enumeration. Cultures were collected by centrifugation at ≈6,000 × g for 10 min and resuspended in phosphate-buffered saline (PBS) to an approximate density of 10^7 to 10^8 CFU/ml. Female C57BL/6J mice were anesthetized with inhaled isoflurane and then inoculated transurethrally with 200 μl of bacterial suspension similar to methods described in Schilling et al. (23). Although the inoculation volume of 200 μl resulted in leakage during and after inoculation, we found that this volume resulted in the most consistent infections.

At the appropriate time points, mice were sacrificed by cervical dislocation after inhalation anesthesia and the bladders and kidneys were harvested. For histologic evaluation, tissue was fixed in neutral buffered formalin and embedded in paraffin. To determine the number of bacteria present in these tissues, bladders or pairs of kidneys were homogenized in 0.025% Triton X-100 in PBS and plated at different dilutions on BHI agar (BactoAgar from BD) supplemented with antibiotics where appropriate. CFU were enumerated after 24 h of incubation at 37°C. Statistical analysis of the kinetic experiment was performed using Student's one-tailed *t* test for correlated samples using the logarithmic values at each time point. When the recovered titers were below the limit of detection, the recovered CFU value was set to 1 for statistical analysis.

Immunohistochemistry. For immunohistochemical analysis of bladder tissue, 5-μm-thick sections were prepared. Sections were deparaffinized using Hemo De (Fisher) (twice for 10 min), rinsed with isopropanol (three times for 3 min) and washed with PBS (three times for 5 min). Tissue sections were blocked with 1% bovine serum albumin, 0.2% nonfat dry milk, and 0.3% Triton X-100 in PBS (PBS-BB) for 15 min at room temperature. Primary antibody raised in rabbit against *Streptococcus* group D antigen (Lee Laboratories) was added in PBS-BB and incubated overnight at 4°C. After PBS washings (three times for 5 min), tissue was incubated with Alexafluor 555-labeled donkey anti-rabbit antibody (Molecular Probes) in PBS-BB and incubated overnight at 4°C. After PBS washes (three times for 5 min), tissue was counterstained with bis-benzimide (Sigma) to reveal nuclear morphology.

Quantitative real-time PCR. Methods were as described in Mysorekar et al. (20) with the following modifications. Female C57BL/6J mice were inoculated transurethrally with 200 μl of PBS, *E. faecalis* 0852, or uropathogenic *E. coli* isolate NU14 grown statically in Luria-Bertani (LB) for 48 h to induce type 1 pilus expression. At the time of sacrifice, kidneys were divided lengthwise, and one half was harvested for RNA isolation and the other half was titered to confirm the presence of bacteria. RNA from infected bladders and kidneys was collected either 6 h or 24 h after infection individually from each mouse using a commercially available affinity matrix-based kit (RNeasy kits, Qiagen). cDNA was generated using random hexamers and quantitative real-time PCR was performed as described (20) using the Bio-Rad iCycler. Primers for amplification of glyceraldehhyde-3-phosphate dehydrogenase, Mip-2, and Socs-3 are as previously described (20).

Competitive infection. Cultures of OG1X and BP78 were resuspended in PBS and mixed in equal volumes to make the mixed inoculum. The BP78 to OG1X ratio was determined by plating the mixed inoculum on medium selective for each strain; 48 h after infection, mice were sacrificed and their bladders and kidneys were collected and homogenized as described above. The homogenate was then plated onto either BHI agar supplemented with streptomycin, to select for OG1X, or tetracycline, to select for BP78. The competition index was calculated similarly to Freter et al. using OG1X as the reference strain (3). Briefly, the competition index = [(CFU of BP78/CFU of OG1X recovered from mice)/(CFU of BP78/CFU of OG1X present in initial inoculum)].

RESULTS

***E. faecalis* can cause a reproducible infection in C57BL/6J mouse kidneys.** In order to study *E. faecalis* cystitis, we inoculated 50 μl of 10^8 CFU of an *E. faecalis* strain, 0852, from a diagnosed urinary tract infection transurethrally into female C57BL/6J mice. This protocol led to inconsistent recovery of bacteria from the bladder but noticeably higher titers in the kidney. Based on this observation, we used a 200-μl inoculum volume to intentionally induce retrograde reflux of the inoculum from the bladder into the kidney (11).

The ability of *E. faecalis* 0852 to persist in bladders and kidneys over a 2-week period is shown in Fig. 1. Fifteen minutes after inoculation, bacterial titers were high in both the bladder and the kidney. *E. faecalis* did not persist in the bladder, as bacterial titers decreased dramatically after 15 min, and many bladders were sterile at later time points. In contrast, recovery of bacteria from the kidneys remained steady over the first 12 h; 24 h after inoculation, bacterial levels in the kidney decreased but nevertheless persisted over a 2-week period. The conclusion from these studies was that *E. faecalis* persisted at higher titers in the kidney than in the bladder over a 2-week time frame (Fig. 1, $P < 0.05$ for five of nine time points, $P < 0.1$ for eight of nine time points).

The large dropoff in bladder titers between 15 min and 6 h was most likely due to the clearance of nonadherent bacteria from the bladder by mechanical forces of urine flow and other innate defenses. The persistence of *E. faecalis* in the kidneys over this time period indicated that the bacteria in the kidney were able to establish residence capable of evading innate defenses. Consistent with this hypothesis was the finding that 16% of mice had recoverable titers of 0852 in the kidneys despite having sterile bladders; conversely, no mice had recoverable bacterial titers in the bladder if their kidneys were

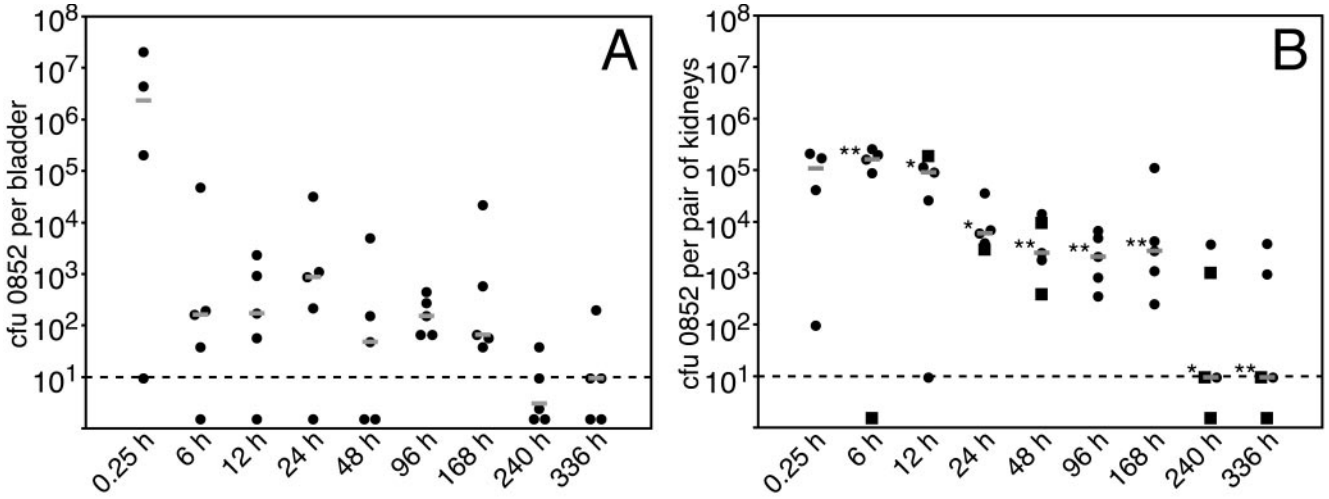

FIG. 1. Kinetics of clearance of *E. faecalis* 0852 from the bladders and kidneys of C57BL/6J mice over 2 weeks. (A) The vast majority of bacteria are quickly cleared from the bladders of mice in the first few hours after infection. (B) Bacteria are found in the kidney immediately after inoculation and are slowly cleared over 2 weeks. Squares represent mice that have sterile bladders. The dashed line represents the limit of detection in this protocol. Horizontal lines represent the median titer at each time ($n = 4$ or 5). A double asterisk (**) indicates that the kidney titer was significantly higher at that time point ($P \leq 0.05$), while a single asterisk (*) indicates $P \leq 0.1$ (paired Student's t test).

sterile (Fig. 1B, squares). Given the variability of CFU per bladder, we hypothesized that bacteria recovered from the bladder at later time points may represent bacteria shed from the kidney. Taken together, the persistence of 0852 in the kidney and its clearance from the bladder suggest that *E. faecalis* has tropism for the kidneys in the urinary tract of C57BL/6J mice.

Multiple *E. faecalis* clinical isolates display tropism for the kidney in the urinary tract of C57BL/6J mice. To determine if the tropism of *E. faecalis* for the kidney in C57BL/6J mice is specific to strain 0852 or whether it represents a general feature of this species, we inoculated mice with five different strains of *E. faecalis* and harvested their bladders and kidneys for titers 48 h after infection (Fig. 2). Two of these strains, B1223 and B1384, were cystitis isolates, and three others, P1503, BP78, and BP250, were pyelonephritis isolates. Consistent with what had been observed with 0852, all of the strains persisted in the kidney to higher levels than in the bladder. Only three mice of the 29 in the group infected with cystitis-derived isolates had more bacteria in the bladder than in the kidney. While this finding may represent an adaptation of the cystitis isolates to have increased adherence to bladder epithelium, the kidney still appeared to have the larger bacterial burden in the majority of mice.

Transurethral inoculation of 0852 results in inflammation in the kidneys but not the bladder. Kidneys and bladders were subjected to histological analysis at various time points following inoculation with *E. faecalis* 0852. Hematoxylin and eosin staining revealed that there was little difference between infected and uninfected bladders at any of the time points examined (6 h, 24 h, 2 days, and 4 days; 24-h time point shown in Fig. 3). In contrast, *E. coli* induces cystitis, as measured by the disruption of the bladder epithelium, marked edema, and recruitment of numerous neutrophils at the same time point (4, 14, 19).

Kidney sections from *E. faecalis*-infected mice, however, showed an inflammatory infiltrate in the renal pelvis. The inflammation was most consistently evident at 24 h after inoculation but was also seen at other time points as small, isolated collections of inflammatory cells. The level of inflammation at 24 h in the kidney was variable, sometimes appearing quite extensive, with inflammatory cells lining the entire pelvis (Fig. 3b and 3e), but small, localized patches of inflammation were

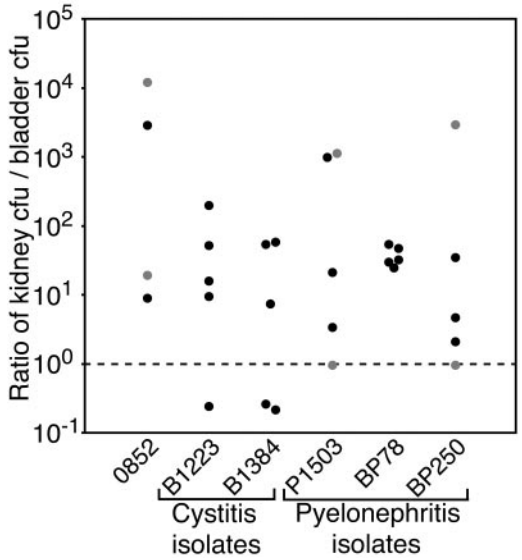

FIG. 2. Recoveries of *E. faecalis* clinical isolates from the kidneys and bladders of mice. Clinical cystitis and pyelonephritis *E. faecalis* isolates were recovered from the bladders and kidneys of infected mice 48 h after infection. The ratio of CFU recovered from the bladder to the CFU recovered from the kidneys in each mouse shows that nearly all mice had more CFU of *E. faecalis* in the kidneys than the bladder ($n = 4$ or 5 for each strain). Gray circles represent mice that have sterile bladders; to calculate the kidney CFU to bladder CFU ratio, the bladder CFU was set to 1. The dashed line represents equal numbers of CFU recovered from bladder and kidney. *E. faecalis* clinical isolates preferentially persist in the kidneys of mice.

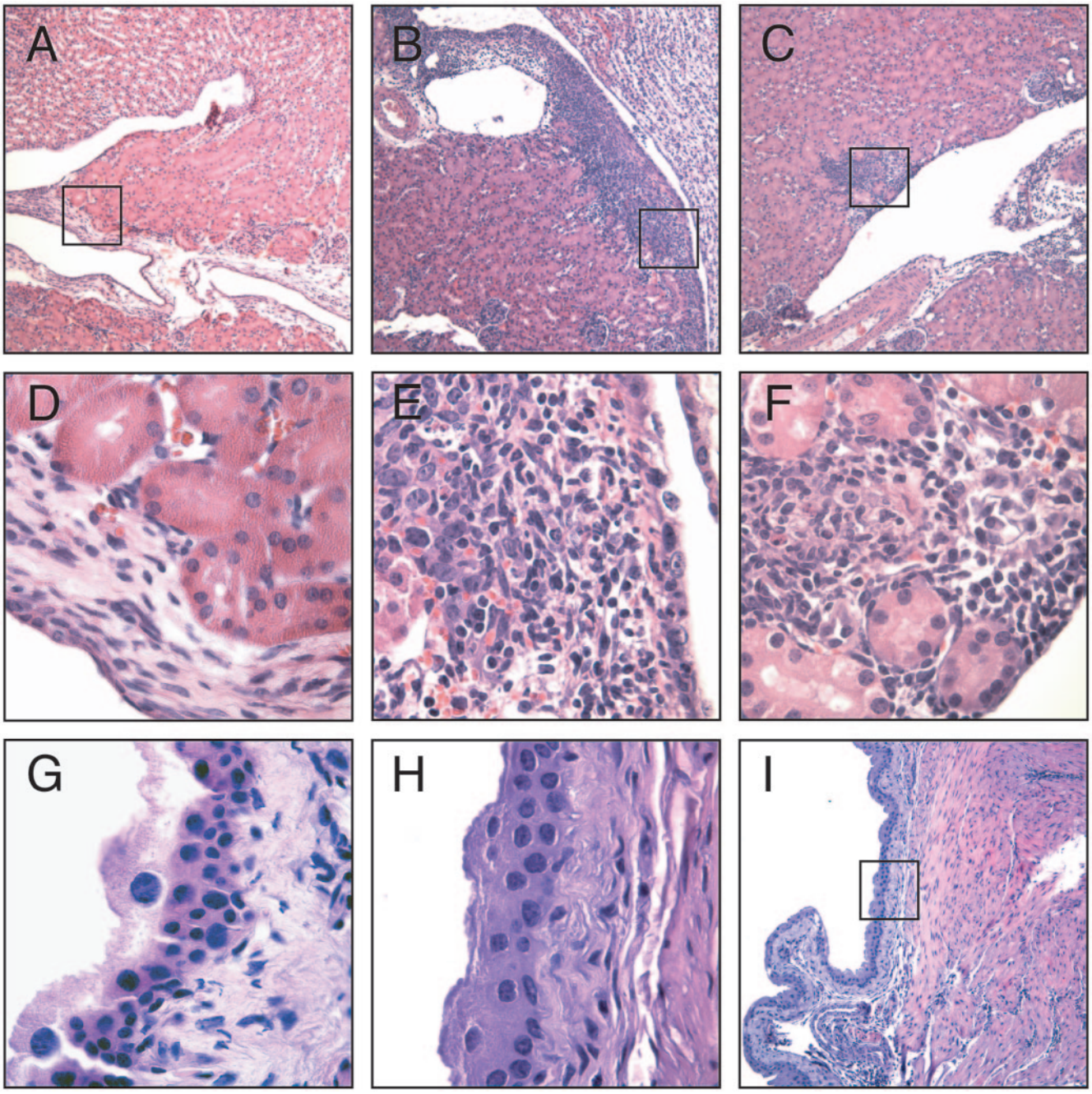

FIG. 3. Light microscopic evaluation of bladders and kidneys in *E. faecalis* 0852-infected mice. Mice were inoculated with either PBS (A, D, and G) or *E. faecalis* 0852 (B, C, E, F, H, and I), and the kidneys (A to F) and bladders (G to I) were harvested 24 h after infection for hematoxylin and eosin staining. An inflammatory response was noted in response to *E. faecalis* in the kidneys (B, C, E, and F) but not the bladder (H and I). Boxed areas in A, B, C, and I (10×) are shown at higher magnification (60×) in D, E, F, and H, respectively.

also observed along the pelvis (as in Fig. 3c and 3f). The cellular infiltrate in the kidneys is primarily monocytic, as determined by histologic features. This is in contrast to the mostly neutrophilic infiltrate seen in *E. coli* pyelonephritis (4). The results of the histologic analysis of the bladder and kidney demonstrate that *E. faecalis* can consistently cause pathology in the kidney but not the bladder, further confirming the tropism of *E. faecalis* for the mouse kidney.

Immunohistochemistry was also utilized to demonstrate the presence of enterococcal antigen within the infected kidney. Using the rabbit Lancefield group D antibody, we showed staining in association with areas of inflammation at 24 h postinfection, demonstrating that the inflammatory cells were recruited in response to the presence of *E. faecalis* rather than damage to the kidney parenchyma by the inoculation procedure (Fig. 4).

Inflammatory markers induced by uropathogenic *E. coli* are not upregulated in the bladder in response to *E. faecalis*. The

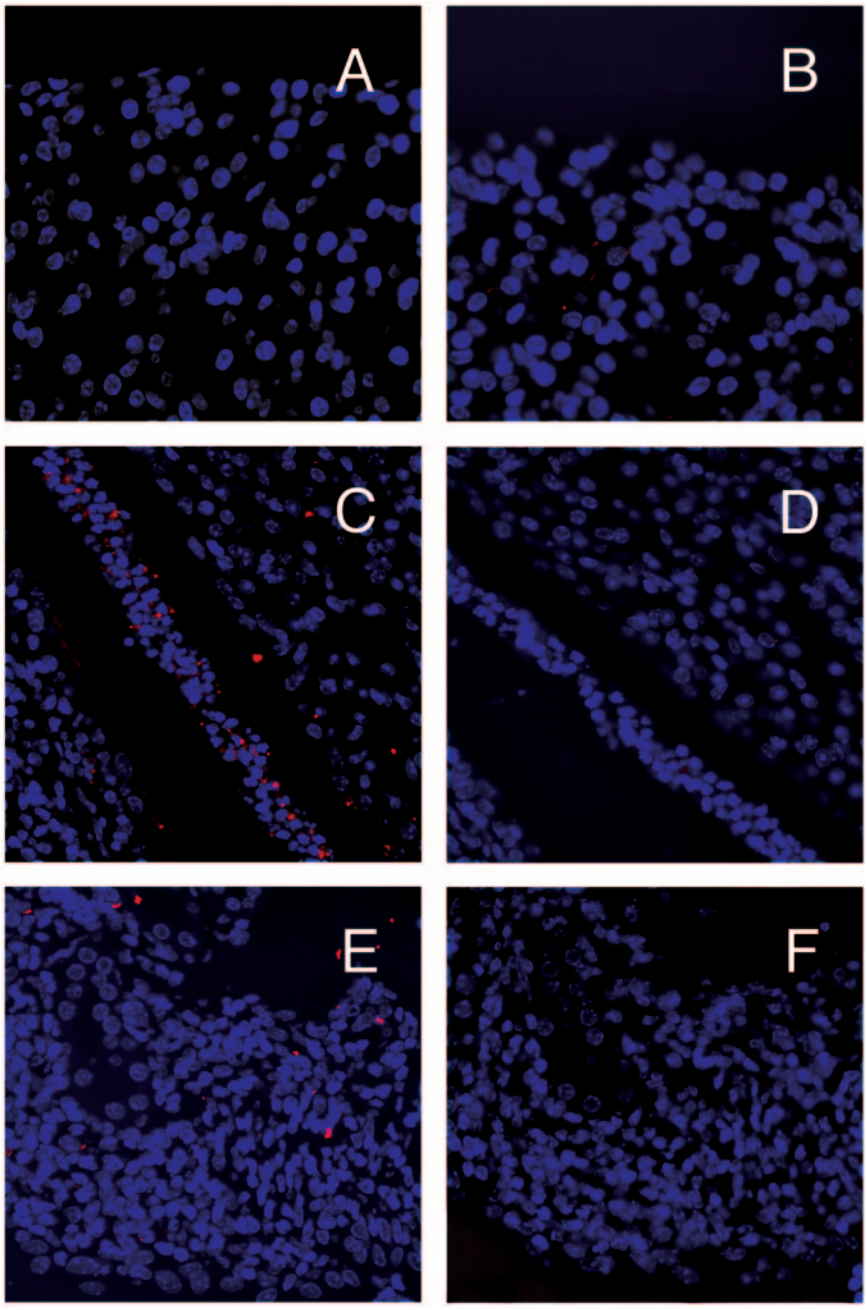

FIG. 4. Lancefield group D antibody immunostaining of *E. faecalis* 0852-infected kidneys 24 h after infection. Kidney sections from mice inoculated with either PBS (A and B) or *E. faecalis* 0852 (C to F) were stained with Lancefield group D antibody (A, C, and E) or an isotype control (B, D, and F). Group D antibody staining was seen mainly in association with inflammatory cells in *E. faecalis*-infected animals. The original magnification for all fields is 20×. Antibody staining is red, and Hoechst nuclear staining is blue.

interaction of uropathogenic *E. coli* with the bladder epithelium results in the expression of a variety of proteins involved in epithelial renewal and immune function (20). Among these, the proinflammatory marker Mip-2, the mouse orthologue to human interleukin-8, and Socs-3, a modulator of cytokine induction, were highly upregulated. We investigated whether *E. faecalis* induced a similar response in the urinary tracts of mice.

E. faecalis 0852- or sham-infected mouse bladders and kidneys were harvested 6 h or 24 h after inoculation, and RNA was collected in order to quantify the relative levels of Mip-2 and Socs-3 by quantitative reverse transcription-PCR. The relative induction of Mip-2 and Socs-3 after infection with NU14 (a clinical uropathogenic *E. coli* isolate) or *E. faecalis* 0852 was investigated (Fig. 5); 24 h after infection with either *E. coli* NU14 or *E. faecalis* 0852, NU14 induced Mip-2 and Socs-3 176-fold and 15-fold, respectively, over *E. faecalis* in the bladder. In the kidney, Mip-2 and Socs-3 were also more strongly induced by *E. coli* NU14 but not to the same magnitude (24-

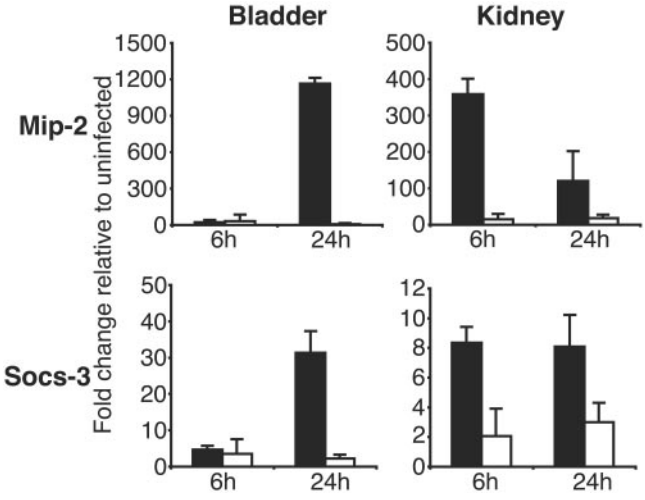

FIG. 5. Quantitative reverse transcription-PCR of inflammatory markers of uropathogenic *E. coli* cystitis strain Mip-2 and Socs-3. The bladders and kidneys of uropathogenic *E. coli*- or *E. faecalis*-infected mice were collected 6 h or 24 h after infection and the RNA was harvested. Quantitative reverse transcription-PCR was performed for Mip-2 and Socs-3 expression levels, and data are normalized to glyceraldehhyde-3-phosphate dehydrogenase (GAPDH) expression. Results are shown as induction relative to a PBS-inoculated control. Induction by uropathogenic *E. coli* strain NU14 (black bars) was consistently higher than that vy *E. faecalis* 0852 (white bars) in both the bladder and kidneys.

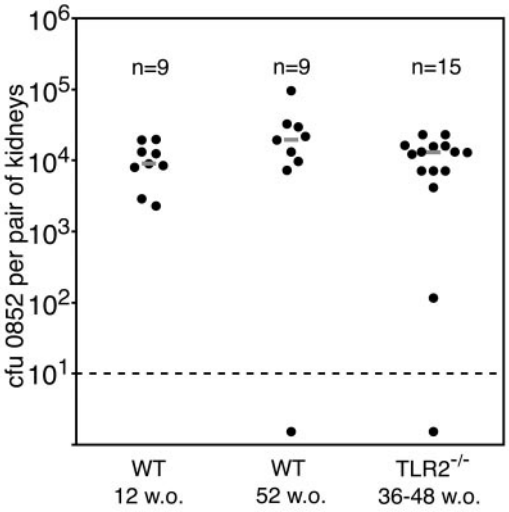

FIG. 6. Effect of TLR2 on the recovery of *E. faecalis* 0852 from the kidneys of mice. C57BL/6J TLR2-deficient mice 36 to 48 weeks old (w.o.) or C57BL/6J wild-type mice 12 weeks old or 52 weeks old were inoculated with *E. faecalis* 0852 and sacrificed 24 h after infection, and the CFU per pair of kidneys were enumerated. TLR2-deficient mice respond comparably to wild-type mice to *E. faecalis* kidney infection.

fold greater induction of Mip-2 and 4-fold greater induction of Socs-3 at 6 h, when the differences were most pronounced). Detection of focal inflammation in the kidney caused by *E. faecalis* may be diluted in this assay, which surveys gene expression levels of the whole kidney. Regardless, the observation that the uropathogenic *E. coli* strain NU14 was a more potent inducer of inflammatory mediators in both the bladder and kidneys implies a distinct pathogenic mechanism for *E. faecalis* in the urinary tract.

Innate response to *E. faecalis* in the kidneys is TLR2 independent. TLR4 has been demonstrated to be an important mediator of the innate host response to *E. coli* urinary tract infections (22, 23). TLR2 has been shown to mediate the host innate response to some gram-positive constituents such as lipoteichoic acid and peptidoglycan (24, 31). To determine if TLR2 plays a role in the initial response to *E. faecalis*, TLR2-deficient C57BL/6 were inoculated with 0852, and kidney titers were compared to wild-type mice 24 h after inoculation. There was no observable difference between the TLR2-deficient mice and the wild-type mice 24 h after infection, indicating that TLR2 did not play a critical role in the innate response (Fig. 6). Histologic examination of TLR2 and wild-type C57BL/6J mice revealed no observable difference in the levels of inflammation between wild-type and mutant mice (data not shown).

Clinically derived *E. faecalis* has a survival advantage over OG1X in the kidneys of mice. To assess the utility of mouse kidney infections as a model system to study pathogenesis of *E. faecalis*, the clinical strain BP78 and the laboratory strain OG1X were inoculated either separately or in a mixed suspension. As shown in Fig. 7a, OG1X and BP78 colonized the bladders and kidneys of mice equally well when infected separately, as determined 48 h after infection. However, in the mixed-infection model, BP78 showed a competitive advantage over OG1X of approximately 10-fold in the kidney, but there was no discernible difference in the bladder (Fig. 7b).

DISCUSSION

Enterococci are usually perceived as commensal bacteria that coexist with their host under most circumstances as part of the normal flora. While not regarded as particularly virulent organisms, enterococci can be significant agents of urinary tract infections in the hospital setting, where patients' defenses can be compromised by catheterization, immune deficiencies, or both. Given that *E. faecalis* is an opportunistic pathogen, animal model systems to study ascending urinary tract infections have been difficult to develop but will be essential for understanding the molecular basis of enterococcal disease.

Two recent studies used an ascending model of urinary tract infections similar to that used for uropathogenic *E. coli* to investigate the function of the Esp and aggregation substance adhesins in the pathogenesis of *E. faecalis* urinary tract infection. A role for aggregation substance has not yet been elucidated, whereas mutations in *esp* reduced colonization of the bladder. An interesting caveat in these studies was that approximately 30% of the mice had sterile bladders even when challenged with wild-type *E. faecalis* (12, 26). These results highlight the need to elucidate the host-pathogen interactions required to maintain robust urinary tract infections with enterococci. Interestingly, both studies noted significant colonization of the kidney tissue despite using a volume of inoculum designed to deliver bacteria only to the bladder.

In the present study, we discovered that *E. faecalis* has tropism for the kidneys in female C57BL/6J mice. This finding was made using a model where the inoculation volume of *E. faecalis* was increased in order to facilitate direct delivery of

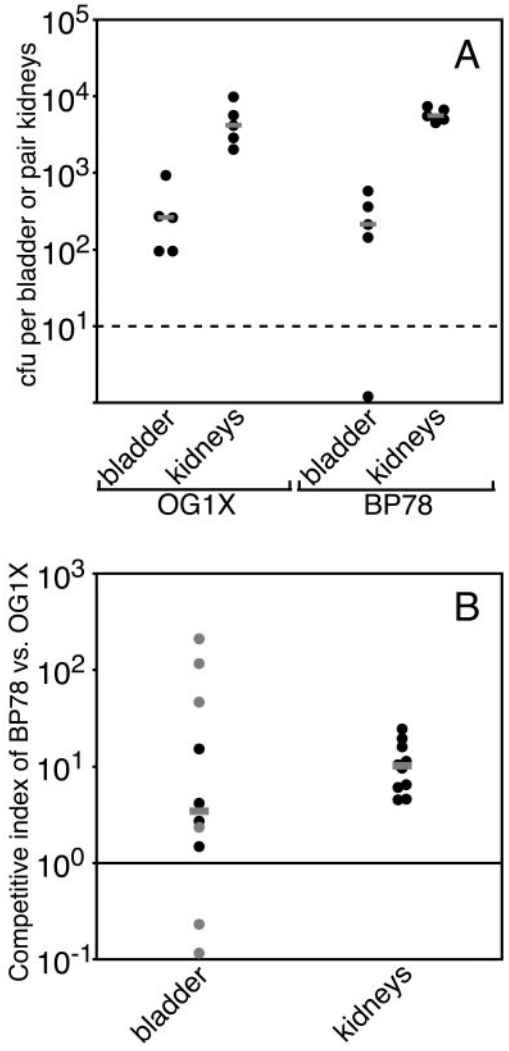

FIG. 7. Competitive infection of a clinical pyelonephritis strain of *E. faecalis*, BP78, and OG1X, a laboratory strain of *E. faecalis*, in the kidneys of mice. (A) Mice were transurethrally inoculated with either OG1X or BP78, and the CFU were enumerated in the bladders and kidneys 48 h after infection. (B) Mice were inoculated with a mixed inoculum of both OG1X and BP78, and the CFU were enumerated 48 h after infection. The competition index (CI) of bacteria recovered from the bladders or kidneys was calculated as described in Materials and Methods. Gray circles represent mice from which only one strain was recovered and the titer was set to 1, so that a competition index could be calculated. During the competitive infection, recovery of BP78 was consistently higher than recovery of OG1X in the kidney.

the bacteria to both the bladder and the kidneys simultaneously. Using this technique, we were able to recover bacteria from >90% of kidneys in mice infected with *E. faecalis*. In the same mice, the bladders were frequently sterile even though the kidneys were colonized. The molecular basis of this tropism for the kidney is unknown. Preferential adherence and/or invasion of *E. faecalis* to kidney versus bladder epithelium is a potential explanation, but host factors involved in innate defenses may also play a role.

The use of cultured bladder cells to study enterococcal pathogenesis in the urinary tract has limitations. Superficial umbrella cells lining the lumen of the bladder have specialized properties, including an ability to assemble uroplakins on their surface. Uroplakins form impermeable plaques that coat the luminal surface of the bladder (15). Cultured epithelial cells are not terminally differentiated, do not assemble uroplakins into plaques, and lack other distinguishing features of superficial umbrella cells, such as their large surface area and pentagonal shape (27). Thus, tropism is best studied in an animal model such as the one described here.

E. faecalis-mediated urinary tract infection appears to occur via a strikingly different mechanism than *E. coli*-mediated urinary tract infection. In a typical *E. coli* urinary tract infection, the bacteria invade the superficial umbrella cells and replicate to high levels, forming intracellular biofilms, a process that induces a TLR4-mediated cytokine response that recruits neutrophils to the site of infection (1, 22). In enterococcal urinary tract infection, there is little to no inflammation in the bladder. Furthermore, neutrophils represented only a minority of the inflammatory cells targeted to the site of infection, which typically is in the kidney. We found that TLR2, which is hypothesized to play a similar role in the innate response to gram-positives as TLR4 does for gram-negative pathogens (28, 29), does not play a substantial role in the innate response to *E. faecalis* in the urinary tract. Several observations reinforce this hypothesis. The presence or absence of TLR2 had no significant impact on the recovery of *E. faecalis* 24 h after infection. A luciferase reporter cell line expressing TLR2 was not stimulated by enterococci (32). Finally, there is substantial evidence that the host uses TLR2-independent pathways to stimulate inflammatory cascades in response to gram-positive infection (2, 5, 17). The recent discovery of TLR11, a Toll-like receptor that specifically recognizes uropathogens, suggested an additional innate mechanism used by the host to respond to enterococci (32).

All six *E. faecalis* strains tested in this study demonstrated the same tropism for the kidney, suggesting that most *E. faecalis* strains contain the core set of virulence factors necessary to cause disease in the kidney. When inoculated separately, OG1X, a commonly used laboratory strain of *E. faecalis* that lacks the recently described enterococcal pathogenicity island (25) and plasmid elements, and BP78, a clinical pyelonephritis isolate, persisted at similar levels over a 48-h period. This implies that OG1X has the essential molecular elements necessary to persist in the kidney. However, in a mixed-competition experiment, BP78 had a survival advantage of approximately 10-fold, suggesting that uropathogenic *E. faecalis* isolates have additional factors that lead to increased fitness in the urinary tract. Thus, mixed-infection experiments proved to be the most sensitive readout of additional virulence factors that enhance persistence in the kidney.

This work raises numerous questions related to human disease. The ability of enterococci to cause disease in the kidney is well established. The diagnosis of upper versus lower urinary tract infection caused by enterococci, as with gram-negative bacilli, is generally based on signs and symptoms. Thus, the presence of fever and flank pain, with or without lower tract symptoms of dysuria, frequency, and urgency suggest upper tract infection (13). Lower tract symptoms without upper tract symptoms are assumed to represent bladder infection, although it has been reported that about 30% of women with

symptoms of bladder infection have silent upper tract infection (13). It will be important to determine whether the findings described in this work can be extended to humans. If enterococci have a strong tropism for the kidney, it is possible that many or most episodes of enterococcal cystitis are due to seeding from an upper tract infection. It is also possible that asymptomatic bacteriuria with enterococci is often localized to the upper tract rather than the bladder. The observation that enterococci fail to elicit a strong induction of inflammatory cytokines in our murine model is consistent with this hypothesis. If enterococcal urinary tract infections are often associated with upper tract infection, there may be treatment implications, since upper tract infection is usually treated for a longer duration than bladder infections (6).

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