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Pilin and Sortase Residues Critical for Endocarditis- and Biofilm-Associated Pilus Biogenesis in Enterococcus faecalis

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Enterococci commonly cause hospital-acquired infections, such as infective endocarditis and catheter-associated urinary tract infections. In animal models of these infections, a long hairlike extracellular protein fiber known as the endocarditis- and biofilm-associated (Ebp) pilus is an important virulence factor for Enterococcus faecalis. For Ebp and other sortase-assembled pili, the pilus-associated sortases are essential for fiber formation as they create covalent isopeptide bonds between the sortase recognition motif and the pilin-like motif of the pilus subunits. However, the molecular requirements governing the incorporation of the three pilus subunits (EbpA, EbpB, and EbpC) have not been investigated in E. faecalis. Here, we show that a Lys residue within the pilin-like motif of the EbpC subunit was necessary for EbpC polymerization. However, incorporation of EbpA into the pilus fiber only required its sortase recognition motif (LPXTG), while incorporation of EbpB only required its pilin-like motif. Only the sortase recognition motif would be required for incorporation of the pilus tip subunit, while incorporation of the base subunit would only require the pilin recognition motif. Thus, these data support a model with EbpA at the tip and EbpB at the base of an EbpC polymer. In addition, the housekeeping sortase, SrtA, was found to process EbpB and its predicted catalytic Cys residue was required for efficient cell wall anchoring of mature Ebp pili. Thus, we have defined molecular interactions involved in fiber polymerization, minor subunit organization, and pilus subcellular compartmentalization in the E. faecalis Ebp pilus system. These studies advance our understanding of unique molecular mechanisms of sortase-assembled pilus biogenesis.

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necessary for assembly of the *E. faecalis* Ebp pilus and incorporation of both the EbpA and EbpB minor subunits (18). Anchoring of pili to the cell wall is often, although not always, achieved by the housekeeping sortase, a conserved, membrane-associated enzyme found in nearly all Gram-positive organisms (19). Like Ebp pili, the *E. faecalis* housekeeping sortase, SrtA (20), is also important for biofilm formation and in animal models of ascending UTI and CAUTI (21–23). However, it is not known whether SrtA participates in the biogenesis of Ebp pili.

Sortase transpeptidation is thought to occur in two steps on the bacterial membrane. First, the enzyme cleaves its substrate between the Thr and Gly residues of the LPXTG-like motif, leading to the formation of a sortase-substrate intermediate with a thio-ester bond between the side-chain sulfur of the sortase catalytic Cys residue and the carbonyl group of the substrate Thr residue. Next, this thioacyl intermediate is resolved upon nucleophilic attack by an acceptor molecule (6, 24, 25). Thus, sortases demonstrate two molecular specificities: (i) for cleavable substrates, partially determined by the substrates’ LPXTG-like motifs and (ii) for acceptor nucleophiles, the basis of which is not fully understood. The housekeeping sortase accepts the cross-bridge peptide of the lipid II cell wall precursor as a nucleophile (26), leading to cell wall anchoring of its substrates. Studies of the *Corynebacterium diphtheriae* pilus islands first suggested that pilus-associated sortases accept conserved Lys residues within pilus structural subunits as nucleophiles, resulting in intermolecular isopeptide bonds formed between pilus subunits. In *C. diphtheria*, the Lys residue in the pilin motif (WXXXVYYPK peptide sequence) of the major pilin, SpaA, is necessary for its polymerization into fibers (12, 27). Canonical pilin motifs are present in N-terminal domains of many sortase-assembled pilus major subunits (6). Similarly, a conserved Lys residue within the minor anchor pilin SpAβ was necessary for its incorporation into pilus fibers (14). Studies in *Actinomyces naeslundii* (28), *Streptococcus pyogenes* (group A streptococci [GAS]) (29), *Streptococcus agalactiae* (group B streptococci [GBS]) (30–32), and *Streptococcus pneumoniae* (the pneumococcus) (33–35) demonstrated that many molecular aspects of sortase-assembled pilus biogenesis are conserved but also revealed unique variations among different systems.

Pilus biogenesis and sortase activity are attractive targets for the development of Gram-positive antivirulence therapies (36). However, a unified understanding of the mechanisms governing these processes is required for rational drug design. The roles of conserved elements of pilus assembly and sortase catalysis, such as sortase recognition motifs, pilin-like motifs, and sortase catalytic residues, have not been directly tested in Ebp pilus biogenesis in *E. faecalis*. Here, we used a panel of strains expressing mutant pilin and sortase alleles to define molecular interactions important for pilus fiber polymerization, minor pilus subunit incorporation, and pilus anchoring to the cell wall. Our results reveal both universal and unique aspects of pilus biogenesis and sortase activity in *E. faecalis*.

**MATERIALS AND METHODS**

**Bacterial growth conditions.** All bacterial strains used in this study are listed in Table S1 in the supplemental material. *Escherichia coli* TOP10 was used for propagation of expression plasmids and grown at 37°C with agitation in Luria-Bertani (LB) broth or agar. For *E. coli* strains carrying plasmids, kanamycin (Kan) was added to growth media at 50 µg ml⁻¹ or ampicillin (Amp) at 25 µg ml⁻¹. *E. faecalis* strains were grown statically at 37°C in Bacto brain heart infusion (BHI) broth or agar supplemented with 25 µg ml⁻¹ of rifampin (Rif) for OG1RF-derived strains or 500 µg ml⁻¹ streptomycin (Str) for OG1X unless otherwise noted. Expression plasmids were maintained in *E. faecalis* by supplementation of growth media with 500 µg ml⁻¹ Kan. All antibiotics were purchased from Sigma-Aldrich Corporation (St. Louis, MO). Media were purchased from BD (Becton, Dickinson and Company, Franklin Lakes, NJ).

**General cloning techniques.** The Ebp pilin amino acid sequence is based on the *E. faecalis* OG1RF sequence for the ebpABC-srtC locus (37), obtained as described previously (10). The SrtA and SecA sequences used in this study are derived from the *E. faecalis* V583 genome (38). The OG1RF and V583 SrtA amino acid sequences are 100% identical. The Wizard genome DNA purification kit (Promega Corp., Madison, WI) was used for isolation of bacterial genomic DNA (gDNA), and the Hurricane Maxi Prep kit (Gared Biotech LLC, Oxford, OH) was used to prepare *E. faecalis* expression plasmid DNA. All plasmids used in the study are listed in Table S2 in the supplemental material. T4 DNA ligase and restriction endonucleases were purchased from New England Biolabs (Ipswitch, MA). PCR was performed with Thunson DNA polymerase from Finnzymes (Thermo Fisher Scientific, Inc., Rockford, IL). The primers used in this study are listed in Table S3.

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To express mutant SrtAΔ200A protein (SrtA with the C200A mutation) in *E. faecalis*, we used splice by overlap extension PCR (SOE-PCR) (39) from *E. faecalis* gDNA to create an sraA open reading frame (ORF) encoding the mutant residue. This ORF was cloned downstream of the rofA promoter in the Gram-positive expression vector pAL1 (40). A DNA fragment upstream of and including the mutation was created by PCR with the forward primer EF3056-f2 (encoding a BamHI restriction site) and the SOE-reverse primer EF3056 C200A-f. A DNA fragment downstream of and including the mutation was created using the SOE forward primer EF3056 C200A-f and the reverse primer EF3056-r3 (encoding a PstI restriction site). Upstream and downstream DNA fragments were spliced by PCR with EF3056-f2 and EF3056-r3. The pAL1::SrtAΔ200A plasmid was derived after digestion of the parent pAL1 plasmid and SOE-PCR products with EcoRI and PstI followed by ligation. All primer sequences are listed in Table S3 in the supplemental material.

We assessed pilus assembly in this study by providing the previously described EbpABC− or EbpABC− SrtC− pilus knockout strains (10) with OG1RF or mutant alleles of the ebp locus in trans. The p-ebpABC and p-ebpABCsrtC expression plasmids (10) encode regions beginning 500 bp upstream of the ebpA translational start codon (as proposed by Nallapreddy et al. [9]) and ending with the ebpC or srtC stop codons, respectively. The plasmids p-ebpABCΔK166A, p-ebpABK170Q, and p-ebpABCΔK200C, encoding putative pilin-like motif mutant alleles of EbpC, EbpB, and EbpA, respectively, were derived by site-directed mutagenesis of p-ebpABC with the Quikchange II kit (Stratagene) using the sense/antisense primer pairs HVN170/HVN171, HVN142/HVN143, and HVN134/HVN135, respectively.

To scramble the EbpB and EbpA LPXTG motifs on expression plasmids, we used SOE-PCR using OG1RF gDNA as a template with the SOE forward/SOE reverse primer pairs HVN220/HVN221 and HVN197/ HVN198, respectively, encoding the mutant sequences. Forward and reverse primers internal to the ebpABC srtC locus and that included restriction sites present in the genome but unique within the locus were designed for these reactions: HVN218/HVN217 and HVN191/HVN192, respectively. The p-ebpABNTPLKsrtC and p-ebpAGTPLBC plasmids were derived by double digestion of the parent plasmids p-ebpABCsrtC and p-ebpABC and the respective SOE-PCR products with EcoRI/StuI or SbfI/AatII, respectively, followed by ligation.

To generate an expression plasmid lacking the ebpA coding sequence, we used SOE-PCR to generate a DNA fragment encoding the region 500 bp upstream of the ebpA translational start codon followed immediately by the ebpB start codon with the SOE forward/SOE reverse primers HVN149/HVN148 encoding the mutant sequence, OG1RF template
are referred to as “membrane” fractions in the text. All bacterial cell fractions were prepared as described previously (10).

For isolation of bacterial cell membranes, cells harvested and washed as described above were stored at −80°C. Cell pellets were thawed on ice and digested in protoplast buffer (20% sucrose, 10 mM Tris-Cl, 50 mM sodium chloride, 1 mM EDTA [pH 8.0]) with 250 μM mutanolytic and 10 mg ml−1 lysozyme (Sigma-Aldrich Corp.) in 1/50 of the original culture volume for 2 h at 37°C. Protoplasts were harvested by centrifugation (−20,000 × g, 20 min, 4°C) and washed once in phosphate-buffered saline (PBS). Cell wall fractions, cell lysates, and culture medium fractions were prepared as described previously (10).

Preparation of protoplast lysates. Bacteria were grown overnight, diluted 1:100 into TSBG (BBL Trypticase soy broth supplemented with 0.25% glucose), and grown statically at 37°C for 8 h. Equal numbers of cells (as determined by optical density at 600 nm [OD600]) were harvested by centrifugation at 5,000 × g for 10 min and washed once in phosphate-buffered saline (PBS). Cell wall fractions, cell lysates, and culture medium fractions were prepared as described previously (10). For isolation of bacterial cell membranes, cells harvested and washed as described above were stored at −80°C. Cell pellets were thawed on ice and digested in protoplast buffer (20% sucrose, 10 mM Tris-Cl, 50 mM sodium chloride, 1 mM EDTA [pH 8.0]) with 250 μM mutanolytic and 10 mg ml−1 lysozyme (Sigma-Aldrich Corp.) in 1/50 of the original culture volume for 2 h at 37°C. Protoplasts were harvested by centrifugation (−20,000 × g, 20 min, 4°C) and washed once in PBS. Washed protoplast pellets were resuspended in 1/5 of the original culture volume of a mixture of 20 mM Tris-HCl (pH 8.0), 150 mM sodium chloride, and 1 mM EDTA with Complete protease inhibitor cocktail (Roche), and cell membranes were disrupted by sonication. The resultant cell lysates were incubated with DNase I (5 μg ml−1) and RNase A (10 μg ml−1) for 15 min on ice. Lysates were then subjected to two successive centrifugations at 15,700 × g for 30 min each at 4°C to remove any unlysed cells or protoplasts. Membranes were then isolated by ultracentrifugation at 165,000 × g for 2 h at 4°C. Pellets containing bacterial membranes were resuspended in ~1/50 the original culture volume of 10 mM Tris-Cl–1 mM EDTA and are referred to as “membrane” fractions in the text. All bacterial cell fractions were stored at −20°C.

Preparation of protoplast lysates. Bacteria were grown, harvested, and washed as for bacterial cell fractionation above. Cell pellets were resuspended in half the original culture volume of protoplast buffer with lysozyme and mutanolytic as described above and incubated at 37°C with agitation. At 0, 1, and 2 h after addition of cell wall hydrolases, a sample from each culture was harvested by centrifugation at 20,000 × g for 5 min and washed in PBS.

Generation of anti-SrtA immune sera. A modified version of E. faecalis V583 SrtA was constructed in which internal amino acid residues 13 to 46, encompassing a transmembrane helix, were deleted (SrtAΔTMH). DNA encoding the modified version of the srtA gene (EF1763) was amplified from V583 gDNA using primers 5′SrtAAttTmMaH and 5′SrtACermHox (listed in Table S3 in the supplemental material) and inserted between the Nhel and Xhol restriction sites of the pET24c plasmid (Novagen). The resultant plasmid (pSJH-C) was transformed into E. coli BL21(DE3)/pLysS, creating strain SJH-469 that was used to transform E. coli BL21(DE3)/pLysS, creating strain SJH-1898. SJH-1898 cells were grown to an OD600 of 0.6, SecA expression was induced with 1 mM IPTG, and cells were grown for another 4 h at 37°C. Cell lysates were prepared by sonication. SecA protein was purified by chromatography using a Talon cobalt affinity column (Clonetech, Mountain View, CA) followed by a Source5Q column (GE Healthcare) connected to an ÄKTA FPLC (Amersham Biosciences Corp.). SecA purity was verified by SDS-PAGE and by N-terminal sequencing. Polyclonal antisera were raised against SrtAΔTMH in rabbits (Agro-Bio, La Ferté-Saint-Aubin, France).

Generation of anti-ScmA immune sera. Full-length E. faecalis V583 secA (EF1763) was amplified from V583 genomic DNA using the primers rSecA-f and rSecA-r (listed in Table S3 in the supplemental material) and inserted between the Ndel and Xhol restriction sites of pET19b (Novagen) for inclusion of an N-terminal His tag. The resulting plasmid (pSJH-9004) was used to transform E. coli BL21(DE3)/pLysS, creating strain SJH-469. The plate resulted plasmid (pSJH-469) was used to transform E. coli BL21(DE3)/pLysS, creating strain SJH-1898. SJH-1898 cells were grown to an OD600 of 0.6, SecA expression was induced with 1 mM IPTG, and cells were grown for another 4 h at 37°C. Cell lysates were prepared by sonication. SecA protein was purified by chromatography using a Talon cobalt affinity column (Clonetech, Mountain View, CA) followed by a Source5Q column (GE Healthcare) connected to an ÄKTA FPLC (Amersham Biosciences Corp.). SecA purity was verified by SDS-PAGE and by N-terminal sequencing. Polyclonal antisera were raised against purified SecA in rabbits (New England Peptide, Gardner, MA). Western blots of SDS-PAGE of SecA purified from E. coli and OG1RF cell lysates probed with the immune sera revealed a single band ~100 kDa. No reactivity of preimmune sera was observed.

Western blots. Bacterial cell fractions described above were diluted in β-mercaptoethanol-containing sample loading buffer and boiled for 10 to 15 min. SDS-PAGE was performed using NuPAGE Novex 3 to 8% Tris-acetate precast protein gels run in morpholinepropane-sulfonic acid (MOPS)-SDS running buffer (Life Technologies Corp.) to detect the pilus prob, or EbpB, SrtA, and SecA monomers. Western blotting was performed as described previously (10) additionally using the anti-ScmA and anti-SrtA immune sera derived here. White space in the figures separates distinct immunoblots or exposures, and lines on a blot show that the lanes were reordered or deleted using Adobe Photoshop CS2 (Adobe Systems, Inc., Mountain View, CA).

Negative-stain immunogold EM. Cells adsorbed to grids were stained with uranyl acetate and incubated with either rabbit (11) or mouse (10) anti-EbpB immune sera followed by the appropriate goat IgG conjugated to either 18-nm or 12-nm colloidal gold particles (Jackson Immunoresearch Laboratories, West Grove, PA). Negative-stain immunogold electron microscopy (EM) was performed as described previously (10).

Deep-etch immunogold electron microscopy. Bacterial cells were grown on TSBG (BBL Trypticase soy broth with 0.25% glucose), and then the cells were centrifuged and washed twice with 1× PBS. Cells were deposited onto glass slides, fixed, and labeled as described previously (42) using rabbit anti-EbpB sera and 18-nm gold bead-conjugated goat anti-rabbit secondary antibody (Jackson Immunoresearch Laboratories, Inc., West Grove, PA). Samples were freeze-dried and imaged as described previously (42).

RESULTS

Deletion of srtA does not affect Ebp pilus polymerization or minor pilin incorporation. To determine the role of the E. faecalis housekeeping sortase SrtA in pilus biogenesis, we examined pilus

Negative-stain immunogold EM. Cells adsorbed to grids were stained with uranyl acetate and incubated with either rabbit (11) or mouse (10) anti-EbpB immune sera followed by the appropriate goat IgG conjugated to either 18-nm or 12-nm colloidal gold particles (Jackson Immunoresearch Laboratories, West Grove, PA). Negative-stain immunogold electron microscopy (EM) was performed as described previously (10).

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Cell wall material was isolated by digestion of strains with cell wall hydrolases followed by centrifugation to remove protoplasts and undigested cells. Pilus HMWs were present in cell wall fractions of OG1RF and the SrtA− strain (data not shown), consistent with previously published results for *E. faecalis* OG1X (40). However, EbpC monomer was also detected in cell wall fractions of the SrtC− SrtA− strain (data not shown), suggesting that some membrane-associated protein copurified with cell wall material for unknown reasons. Possibly, EbpC-containing sites of pilus assembly in the membrane of *E. faecalis* are intimately associated with the cell wall. Thus, we could not determine whether pili detected in cell wall fractions of the SrtA− strain were anchored to the cell wall, potentially by another factor, such as SrtC, or membrane associated but copurifying with cell wall material.

Substrates of the housekeeping sortases, including the sortase-assembled pili of *C. diphtheriae* (44), are often found in culture supernatants and not in cell wall fractions in the absence of the enzyme for unknown reasons. Thus, we performed Western blot analysis of filter-sterilized culture supernatants. Although, we detected pilus HMWs in supernatants of the SrtA− strain, similar amounts were also present in OG1RF supernatants (Fig. 1A). The mechanism leading to detection of pili in supernatants of these two strains is unknown but was not affected in the absence of SrtA.

To further investigate the effect of the srtA deletion on pilus subcellular compartmentalization, we next performed Western blotting of protoplast lysates, the pelleted cellular material remaining after progressive depletion of cell wall material by digestion with lysozyme and mutanolysin for up to 2 h. No pilus HMWs were observed associated with OG1RF protoplasts after only 1 h of cell wall hydrolase treatment (Fig. 1B, left), arguing that all of the pili were anchored to the cell wall and released by this treatment. As expected, hydrolase treatment did not affect the presence of EbpC monomers in SrtC− SrtA− protoplas (Fig. 1B, right). For unknown reasons, pilin monomers were consistently detected as doublets on SDS-PAGE, as seen for EbpC in Fig. 1B (right panel). Similarly, pilus HMWs were still observed after 2 h of hydrolase treatment of the SrtA− strain (Fig. 1B, middle), suggesting that in the absence of SrtA, pili were retained in the bacterial cell membrane where pilus assembly occurs. Notably, the SrtA− strain consistently produced more pili than OG1RF (compare the 0-h lanes of OG1RF and the SrtA− mutant in Fig. 1B). Although we cannot rule out the possibility that some pili in the SrtA− mutant are linked to the cell wall, as discussed above, this increased pilus expression may contribute to copurification of membrane-associated pili with cell wall fractions in the SrtA− strain.

**Pili produced by SrtA mutants accumulate in bacterial cell membranes.** To further investigate the role of SrtA in Ebp pilus subcellular localization, we isolated bacterial cell membranes from OG1RF and the SrtA−, SrtA−/pAL1 (vector control strain), and SrtA−/pAL1::srtA strains. The previously described pAL1::srtA plasmid encodes an OG1 allele of srtA under the control of the GAS rofA promoter (40), which complements pilus production in OG1RF SrtA− to levels similar to WT and does not affect the subcellular localization of the Ebp pilus, as judged by EM (data not shown). A vector control plasmid, pAL1, has the coding region for the GAS alkaline phosphatase PhoZ under the control of the rofA promoter (40). Western blots of membrane fractions probed with anti-EbpC sera revealed pilus HMWs only in membranes isolated from the SrtA− and SrtA−/pAL1 strains but not in...
those from OG1RF or the SrtA-/-pAL1:SrtA strain (Fig. 2A, top blot). Thus, lack of SrtA resulted in accumulation of pili in bacterial cell membranes, consistent with our above observation that the SrtA- strain pili were present in a bacterial cell compartment protected from treatment with cell wall hydrolases. Western blots performed on the same samples using antisera generated against the SecA membrane protein (Fig. 2A, middle blot) and SrtA (Fig. 2A, bottom blot) revealed that equal amounts of membrane material were isolated and analyzed for each strain and that SrtA was expressed in OG1RF and the SrtA-/-pAL1:SrtA strain.

To determine whether lack of the SrtA protein or lack of its catalytic activity resulted in the observed membrane accumulation of pili in strains lacking SrtA, we mutated the predicted SrtA catalytic Cys 200 residue to Ala on the pAL1::SrtA expression plasmid, resulting in the plasmid pAL1::SrtAC200A. The SrtA and SrtAC200A alleles were expressed to similar levels from the pAL1 plasmid backbone in whole-cell lysates (Fig. 2B) and membrane fractions (Fig. 2A, bottom blot). Membranes isolated from the SrtAC200A strain carrying either pAL1:vector control) or pAL1::SrtA were probed with the indicated anti-pilin sera. The symbol # shows the EbpB monomer released mainly to culture supernatants of the SrtC- strain. The asterisk shows the larger EbpB monomer primarily associated with cells in strains lacking SrtA.

EbpA monomers did not differ between the two strains (Fig. 3A, top and bottom blots, respectively). However, the EbpB monomer migrated at a higher molecular mass (50 kDa) on SDS-PAGE in cell lysates of the SrtC- SrtA- mutant (Fig. 3A, asterisk) than in lysates of the SrtC- mutant, consistent with the posttranslational cleavage of the EbpB CWSS (46 kDa) only in the presence of SrtA. This phenotype was complemented by transformation of the SrtC- SrtA- mutant with pAL1::SrtA but not with pAL1. Furthermore, greater EbpB monomer signal was observed in cell lysates of strains lacking SrtA than in those of strains expressing SrtA (Fig. 3A, middle blot). EbpB monomers were primarily detected in culture supernatants of the SrtC- strain but not in those of the SrtC- SrtA- mutant (Fig. 3B, #), suggesting that sorting of EbpB to the culture medium depended on its processing by SrtA. Taken together, these results suggest that EbpB, but not EbpC or EbpA, is an SrtA substrate.

EbpC's pilin-like motif Lys 186 is necessary for EbpC fiber polymerization. The next aspect of pilus biogenesis we examined was fiber polymerization. In E. faecalis, EbpC is the only structural subunit necessary (9) and sufficient (10) for Ebp polymerization. To test whether the EbpC pilin-like motif (ELAVVHITYPK [conserved residues are underlined]) (9) was involved in fiber polymerization, we mutated the Lys 186 residue, predicted to participate in sortase formation of interpilin isopeptide bonds, to Ala on the expression plasmid p-ebpABC. This plasmid contains the OG1RF ebp locus beginning 500 bp upstream of ebpA's translational start codon to include the native promoter and ending with the ebpC stop codon. We have previously shown that a chromosomal deletion mutant lacking all of the Ebp structural subunit coding regions complemented with p-ebpABC (EbpABC with p-ebpABC) polymerizes pili similar to those of OG1RF (10). We examined pilus assembly in the EbpABC- strain carrying p-ebpABC or the mutant plasmid (p-ebpABCK186A) using negative-stain immunogold electron microscopy (EM) and Western blot analyses. Bacterial cells with pilus fibers decorated with gold beads were visible by EM from cultures of the EbpABC-
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ebpABC mutant, but not from cultures of the EbpABC+/pGCP123 strain (vector control strain) or EbpABC+/p-ebpABCK186A strain (Fig. 4A), showing that the EbpC pilin-like motif Lys 186 was necessary for pilus fiber elaboration. Western blots of cell lysates of the EbpABC−/p-ebpABC strain probed with anti-EbpC immune sera revealed pilus HMWs (Fig. 4B, brackets), indicating EbpC polymerization. Likewise, HMWs were observed on Western blots of EbpABC−/p-ebpABC cell lysates developed with anti-EbpB and anti-EbpA sera (Fig. 4C and 4D, brackets), indicating incorporation of EbpB and EbpA into pilus fibers, respectively. In contrast, no HMWs were visible on Western blots of cell lysates or culture supernatants (data not shown) of EbpABC−/p-ebpABCK186A cells probed with any antipilin sera (Fig. 4B to D, top blots), showing that the EbpC pilin-like motif Lys 186 is necessary for EbpC polymerization into fibers.

**Mutation of EbpC Lys 186 affects EbpC and EbpA expression.** Although not seen in cell lysates of strain OG1RF (data not shown), we observed EbpC monomers (Fig. 4B and see Fig. 6B, bottom blots) and EbpA monomers (Fig. 6D, bottom blot) in cell lysates of the EbpABC−/p-ebpABC strain. We hypothesize that pilin production from the multicopy plasmid may saturate the capacity of SrtC produced from a single copy on the chromosome, leading to the presence of unprocessed pilin monomers in cell lysates. EbpB monomers were seen in culture supernatants (Fig. 4C, bottom blot), consistent with previously published results for OG1RF (10). Similarly, EbpB monomers were observed in the culture supernatants of the EbpABC−/p-ebpABCK186A strain (Fig. 4C, bottom blot), showing that mutation of EbpC Lys 186 did not affect EbpB expression or processing. Although EbpA and EbpC K186A monomers were expressed by EbpABC−/p-ebpABCK186A cells, they migrated differently on reducing SDS-PAGE and localized differently than those from EbpABC−/p-ebpABC cells. The EbpC K186A monomer shifted to a lower molecular mass (Fig. 4B, #). We hypothesize that the sortase recognition motif of the EbpCK186A monomer (LPSTG) was cleaved by SrtC, leading to the observed downward shift on SDS-PAGE due to the loss of the CWSS. Thus, we hypothesized that the EbpA species found in supernatants of the EbpABC−/p-ebpABCK186A strain arose after EbpA processing by SrtC. Possibly, an EbpA-SrtC thioacyl intermediate could not be resolved in the absence of the EbpC Lys 186 nucleophile, leading to hydrolysis of the thioester bond and release of processed EbpA into the extracellular milieu, where it may have undergone proteolytic degradation, resulting in the observed EbpA species.

**EbpB’s pilin-like motif Lys 179 is necessary for its incorporation into pili.** We have previously shown that deletion of ebpB does not affect EbpC polymerization or incorporation of EbpA into pilus fibers (10), demonstrating the role of EbpB as an ancillary pilus subunit. Incorporation of minor subunits into sortase-assembled pilus fibers of other systems requires either a conserved Lys residue or LPXTG-like motif, depending on the pilin’s location within the pilus fiber (6, 43, 45). EbpB encodes a pilin-like motif (SLTHILYPK) with a conserved Lys residue (9). We investigated the importance of EbpB’s pilin-like motif in Ebp pilus assembly by mutating Lys 179 to Ala on the expression plasmid p-ebpABC and assessing pilus assembly by the mutant plasmid p-ebpABCK179A using the analyses described above. Gold bead-decorated fibers were observed on bacterial cells from cultures of EbpABC−/p-ebpABCK179A cells in immunogold EM studies using anti-EbpC antisera, similar to those from cultures of EbpABC−/p-ebpABC cells. The EbpC K186A monomer shifted to a lower molecular mass (Fig. 4B, #). We hypothesize that the sortase recognition motif of the EbpCK186A monomer (LPSTG) was cleaved by SrtC, leading to the observed downward shift on SDS-PAGE due to the loss of the CWSS. Thus, we hypothesized that the EbpA species found in supernatants of the EbpABC−/p-ebpABCK186A strain arose after EbpA processing by SrtC. Possibly, an EbpA-SrtC thioacyl intermediate could not be resolved in the absence of the EbpC Lys 186 nucleophile, leading to hydrolysis of the thioester bond and release of processed EbpA into the extracellular milieu, where it may have undergone proteolytic degradation, resulting in the observed EbpA species.

**EbpB’s pilin-like motif Lys 179 is necessary for its incorporation into pili.** We have previously shown that deletion of ebpB does not affect EbpC polymerization or incorporation of EbpA into pilus fibers (10), demonstrating the role of EbpB as an ancillary pilus subunit. Incorporation of minor subunits into sortase-assembled pilus fibers of other systems requires either a conserved Lys residue or LPXTG-like motif, depending on the pilin’s location within the pilus fiber (6, 43, 45). EbpB encodes a pilin-like motif (SLTHILYPK) with a conserved Lys residue (9). We investigated the importance of EbpB’s pilin-like motif in Ebp pilus assembly by mutating Lys 179 to Ala on the expression plasmid p-ebpABC and assessing pilus assembly by the mutant plasmid p-ebpABCK179A using the analyses described above. Gold bead-decorated fibers were observed on bacterial cells from cultures of EbpABC−/p-ebpABCK179A cells in immunogold EM studies using anti-EbpC antisera, similar to those from cultures of EbpABC−/p-ebpABC cells. The EbpC K186A monomer shifted to a lower molecular mass (Fig. 4B, #). We hypothesize that the sortase recognition motif of the EbpCK186A monomer (LPSTG) was cleaved by SrtC, leading to the observed downward shift on SDS-PAGE due to the loss of the CWSS. Thus, we hypothesized that the EbpA species found in supernatants of the EbpABC−/p-ebpABCK186A strain arose after EbpA processing by SrtC. Possibly, an EbpA-SrtC thioacyl intermediate could not be resolved in the absence of the EbpC Lys 186 nucleophile, leading to hydrolysis of the thioester bond and release of processed EbpA into the extracellular milieu, where it may have undergone proteolytic degradation, resulting in the observed EbpA species.

**EbpB’s pilin-like motif Lys 179 is necessary for its incorporation into pili.** We have previously shown that deletion of ebpB does not affect EbpC polymerization or incorporation of EbpA into pilus fibers (10), demonstrating the role of EbpB as an ancillary pilus subunit. Incorporation of minor subunits into sortase-assembled pilus fibers of other systems requires either a conserved Lys residue or LPXTG-like motif, depending on the pilin’s location within the pilus fiber (6, 43, 45). EbpB encodes a pilin-like motif (SLTHILYPK) with a conserved Lys residue (9). We investigated the importance of EbpB’s pilin-like motif in Ebp pilus assembly by mutating Lys 179 to Ala on the expression plasmid p-ebpABC and assessing pilus assembly by the mutant plasmid p-ebpABCK179A using the analyses described above. Gold bead-decorated fibers were observed on bacterial cells from cultures of EbpABC−/p-ebpABCK179A cells in immunogold EM studies using anti-EbpC antisera, similar to those from cultures of EbpABC−/p-ebpABC cells. The EbpC K186A monomer shifted to a lower molecular mass (Fig. 4B, #). We hypothesize that the sortase recognition motif of the EbpCK186A monomer (LPSTG) was cleaved by SrtC, leading to the observed downward shift on SDS-PAGE due to the loss of the CWSS. Thus, we hypothesized that the EbpA species found in supernatants of the EbpABC−/p-ebpABCK186A strain arose after EbpA processing by SrtC. Possibly, an EbpA-SrtC thioacyl intermediate could not be resolved in the absence of the EbpC Lys 186 nucleophile, leading to hydrolysis of the thioester bond and release of processed EbpA into the extracellular milieu, where it may have undergone proteolytic degradation, resulting in the observed EbpA species.
its expression or sorting to the culture medium but did prevent EbpB incorporation into pili.

**EbpB’s sortase recognition motif is dispensable for its incorporation into pili.** We determined the importance of the EbpB Leu-Pro-Lys-Thr-Asn predicted sortase recognition motif in pili assembly by replacing the OG1RF sequence (LPKTN) with a scrambled sequence (NTPLK) on the expression plasmid p-ebpABC, which contains the OG1RF ebp locus beginning 500 bp upstream of ebpA’s translational start codon and ending with the srtC stop codon. Pilus assembly by the mutant plasmid (p-ebpABNTPLK) was examined as described above. In immunogold EM studies, bacterial cells with gold bead-decorated fibers were observed in cultures of the EbpABC−SrtC− strain carrying either pGCP123 (vector control), p-ebpABCsrtC, or p-ebpABNTPLKsrtC. (A) Scale bars are 500 nm. Blots were probed with (B) anti-EbpC, (C) anti-EbpB, or (D) anti-EbpA immune sera. Pus HMWs are indicated with brackets.

![Figure 5](http://jb.asm.org/)

**FIG 5** EbpB’s sortase recognition motif is dispensable for EbpB incorporation into pili fibers. (A) Negative-stain immunogold EM using anti-EbpC sera and (B to D) Western blot analyses of cell lysates were performed on the EbpABC−SrtC− strain carrying either pGCP123 (vector control), p-ebpABCsrtC, or p-ebpABNTPLKsrtC. (A) Scale bars are 500 nm. Blots were probed with (B) anti-EbpC, (C) anti-EbpB, or (D) anti-EbpA immune sera. Pus HMWs are indicated with brackets.

a mutant lacking EbpB (10). Thus, EbpB incorporation into pilus fibers relies on the Lys residue of its pilin-like motif but does not require its LPKTN sortase recognition motif, consistent with localization of EbpB at the pilus base.

**EbpA’s Lys 978 is dispensable for its incorporation into pili fibers.** We have previously shown that deletion of ebpA does not prevent EbpC polymerization or EbpB expression (10), confirming its role as a minor pilin. Although EbpA does not encode a canonical pilin motif, Nallapareddy et al. predicted a noncanonical pilin motif in EbpA that included Lys 978 (KYGIEHYAGK) (9). We mutated this Lys to Ala on the expression plasmid p-ebpABC and assessed the ability of the EbpABC−strain carrying either the parent p-ebpABC plasmid or the mutant p-ebpA^K978A/ABC plasmid to assemble pili. No difference was observed in the ability of either EbpA or EbpA^K978A to incorporate into pilus HMWs on Western blots (data not shown).

**EbpA’s sortase recognition motif is necessary for its incorporation into pili.** To determine the role of EbpA’s Leu-Pro-Glu-Thr-Gly predicted sortase recognition motif in pilus assembly, we replaced the OG1RF motif (LPETG) with a scrambled motif (GTPLE) on the p-ebpABC expression plasmid and assessed pilus assembly by the mutant plasmid (p-ebpAGTPLEBC), as described above. Using anti-EbpC antiserum, gold bead-decorated pilus fibers were observed in immunogold EM studies of bacterial cells from cultures of EbpABC− cells carrying either p-ebpABC or p-ebpAGTPLEBC but not cultures of EbpABC−/pGCP123 cells (Fig. 6A), showing that the EbpA LPETG sortase recognition motif was dispensable for pilus fiber elaboration. Western blots of cell lysates of the EbpABC− strain carrying either p-ebpABC or p-ebpAGTPLEBC developed with anti-EbpC or anti-EbpB sera revealed pilus HMWs (Fig. 6B and C, top blots), indicating no defect in EbpC polymerization or EbpB incorporation. However, when blots were developed with anti-EbpA sera, HMWs were observed only from cell lysates of the EbpABC−/p-ebpABC strain but not from those of the EbpABC−/p-ebpAGTPLEBC strain (Fig. 6D, top blot), demonstrating that EbpA was not incorporated into pilus fibers in the latter strain. Similar EbpA low-molecular weight ladder (LMW) species were visible in cell lysates of both strains (Fig. 6D, open arrowheads), showing that EbpA expression was unaffected by the scrambled motif. Thus, in contrast to EbpB, EbpA incorporation into pilus fibers relies on its sortase recognition motif, consistent with its predicted localization to the pilus tip. We further confirmed that EbpA is located on the tip by deep-etch immunogold EM (Fig. 6E). If EbpA acted as a nucleophile in any sortase transpeptidation reaction, we would have expected to detect EbpA still incorporated into pilus HMWs in the EbpABC−/p-ebpAGTPLEBC strain via this mechanism, just as we detected EbpB in pili of the EbpABC− SrtC−/p-ebpABNTPLKsrtC strain. Although EbpA contains Lys residues apart from Lys 978, the complete dissociation of EbpA with a scrambled sortase recognition motif from pili strongly suggests that none of these residues participates in sortase transpeptidation in *E. faecalis*.

**EbpA protein is dispensable for normal pilus assembly.** We previously showed that pilus from the ebpA deletion mutant EbpA and EbpAB− strains exhibited a perturbed morphology that manifested as compressed EbpC bands on SDS-PAGE and longer EbpC fibers visible in EM studies (10). We hypothesized that this altered pilus morphology resulted from cis effects of the ebpA deletion allele since expression of EbpA in trans did not restore normal pilus expression (10). Consistent with this hypoth-
esis, our results above showed that pili lacking the EbpA protein in the EbpABC/p-ebpA^{GTPLE}BC strain exhibited the normal morphology. To confirm this, we created an expression plasmid with only the EbpB and EbpC structural subunit coding regions (p-ebpBCsrtC) and examined pilus assembly as described above. Using anti-EbpC antisera, bacterial cells with gold bead-decorated pilus fibers were observed in immunogold EM studies of the 

EbpABC^{SrtC} strain carrying either p-ebpABCsrtC or p-ebpBCsrtC (Fig. 7A). Furthermore, Western blots of cell lysates and culture supernatants of the EbpABC^{SrtC} strain carrying either p-ebpABCsrtC or p-ebpBCsrtC were performed after SDS-PAGE of the indicated cell fractions with (B) anti-EbpC or (C) anti-EbpB immune sera. Pilus HMWs are indicated with brackets.

FIG 6 EbpA’s sortase recognition motif is necessary for EbpA incorporation into pilus fibers and for EbpA’s localization at the fiber. (A) Negative-stain immunogold EM studies were carried out with anti-EbpC sera to visualize pilus fibers expressed by the EbpABC strain carrying either pGCP123 (vector control), p-ebpABC, or p-ebpA^{GTPLE}BC. Scale bars are 500 nm. Western blots (B to D) of the EbpABC strain carrying either pGCP123 (vector control), p-ebpABC, or p-ebpA^{GTPLE}BC were performed after SDS-PAGE of the indicated cell fractions with (B) anti-EbpC, (C) anti-EbpB, and (D) anti-EbpA immune sera. The top blots show pilus HMWs (brackets), while the bottom blots show pilin monomers (arrowheads, EbpAGTPLE). (E) Deep-etch immunogold EM was performed with anti-EbpA sera to determine the localization of EbpA in the pilus fiber. Solid arrowheads indicate gold beads. Scale bars are 100 nm.
tiated by SrtC cleavage of the EbpA LPETG sortase recognition motif. The pilin-like motif Lys 186 of EbpC acts as nucleophile to resolve the resultant EbpA-SrtC thioacyl intermediate, leading to incorporation of EbpA at the tips of pili (Fig. 8B). (ii) Pilus polymerization occurs as growing pilus fibers activated by SrtC cleavage of the most recently added subunit (EbpA-EbpC\(_n\)-SrtC thioacyl intermediates) are also resolved upon nucleophilic attack by EbpC Lys 186 (Fig. 8C). (iii) EbpB incorporation is achieved when a growing fiber activated by SrtC cleavage is instead resolved by the EbpB pilin-like motif Lys 179. Fully assembled pili comprising all subunits are thus tethered to the bacterial cell membrane via the hydrophobic domain of the EbpB CWSS (Fig. 8D). SrtC processing of EbpB would permit continued fiber polymerization. Alternatively, these fibers may be activated by SrtA cleavage of the EbpB LPKTN sortase recognition motif. (iv) Sorting of pili to the cell wall then likely occurs when SrtA-activated pilus fibers (EbpA-EbpC\(_n\)-EbpB-SrtA thioacyl intermediates) are resolved by the lipid II cell wall precursor (Fig. 8E).

Evidence for the model includes our data showing that mutation of the EbpC pilin-like motif Lys 186 abrogates EbpC...
polymization, consistent with results from *C. diphtheriae*, *Bacillus*, and other sortase-assembled pilus systems. Strong evidence for the role of the major subunit pilin motif as an acceptor nucleophile for the pilus-associated sortase(s) comes from mass spectrometry studies by Budzik et al. in *Bacillus* that isolated and identified nonconsecutive peptides encompassing intermolecular isopeptide bonds (i) between two major pilins (17) and (ii) between a minor tip pilin and a major pilin (52).

Analysis of the EbpABC−/p-ebpABC<sub>K186A</sub> strain expressing the nonpolymerizing EbpC<sub>K186A</sub> protein led to insights into pilus assembly beyond identification of the SrtC acceptor nucleophile. Our results suggested that SrtC cleaved both the EbpA and EbpC LPXTG-like motifs in this strain. Although mutation of the EbpC Lys 186 prevented SrtC's acceptance of EbpC as a nucleophile, namely, EbpA-EbpB and EbpC-EbpB heterodimerization. We previously demonstrated that a putative SrtC-dependent EbpA-EbpB heterodimer forms in the absence of EbpC (10), and here we observed a probable EbpC-EbpB heterodimer formed in the absence of EbpA. However, no pilin heterodimers were observed in the EbpABC−/p-ebpABC<sub>K186A</sub> strain, suggesting that mutation of the EbpC pilin-like motif somehow prevented nucleophilic attack by the EbpB pilin-like motif Lys 179. We hypothesize that local disruption of SrtC activity was caused by an accumulation of mutant EbpC<sub>K186A</sub> protein. Indeed, we have previously shown that SrtC and thus pilus assembly occurs in distinct membrane domains on the bacterial cell and that EbpA and EbpC focally accumulate in the membrane in the absence of SrtC (40). We suspect that EbpC<sub>K186A</sub> also accumulates within these membrane domains since pilus polymerization, and thus appropriate sorting of EbpC<sub>K186A</sub>, was prevented. Here, EbpC<sub>K186A</sub> may titrate SrtC enzymatic activity or sterically hinder access of SrtC to other pilins.

Our mutational analyses of the minor subunit pilin-like and LPXTG-like motifs also support the proposed model of Ebp pilus assembly. The EbpA LPETG motif was necessary for its incorporation into pili, while its pilin-like motif Lys 978 was dispensable, consistent with the predicted molecular requirements for a tip pilin. Additionally, deep-etch immunogold EM revealed that EbpA is indeed localized at the tip, consistent with our mutational analysis. Localization of a dedicated functional subunit to the distal end of a pilus fiber is a common characteristic of bacterial pilins, including the type 1 pilus necessary for uropathogenic *E. coli* pathogenesis in UTI (53). We recently showed that a metal ion-independent adhesion site (MIDAS) motif encoded within the predicted von Willebrand factor A (VWA) domain of EbpA is necessary for Ebp pilus function in a mouse model of enterococcal CAUTI.

Conversely, the EbpB LPKTN motif was dispensable for its incorporation into pili, while its pilin-like motif Lys 179 was necessary, consistent with the molecular requirements for a base pilin. Similarly, incorporation of the SpaB base pilin of *C. diphtheriae* depended on a conserved Lys residue, although not encoded within canonical pilin motif, but not the SpaB sortase recognition motif (14). We additionally demonstrated that EbpB, but not EbpA or EbpC, was processed by SrtA in the absence of SrtC, providing further evidence for terminal incorporation of EbpB since it is thought that cell wall anchoring of pili must occur via the cell-proximal pilus subunit. It is possible, however, that EbpB may also be cleaved by SrtC, and thus incorporated within the pilus shaft in addition to its localization to the base. Recently, Linke et al. crystallized the putative FctB anchor pilin from the GAS 90/3065 strain and proposed that an enrichment of Pro residues just N terminal to the CWSS provides important rigidity for the cell wall anchoring pilus subunit (54). EbpB has no such clustering of Pro residues, suggesting this structural component of the base pilin is not universal among sortase-assembled pili.

The role of the housekeeping sortase in pilus biogenesis seems to vary among sortase-assembled pilus systems. In *S. pneumoniae*, deletion of the housekeeping sortase alone does not affect pilus fiber sorting to the cell wall, as determined by Western blots of cell wall fractions (55, 56), suggesting that pilus-associated sortases anchor fibers to the cell wall in the absence of the housekeeping sortase. In contrast, in *C. diphtheriae*, deletion of the housekeeping sortase (SrtF) leads to missorting of pilus fibers to the culture medium instead of the cell wall (44). In *E. faecalis*, we did not detect changes in the quantity of pili in cell wall or culture medium fractions in the absence of SrtA. Instead, we observed an accumulation of pili in the bacterial cell membrane, the site of pilus assembly, likely representing an intermediate stage of pilus biogenesis trapped in the absence of SrtA. Furthermore, we provide evidence that SrtA processes EbpB, which may represent the mechanism of pili anchoring to the cell wall. Paradoxically, in our hands, pilus HMWs were detected by Western blotting in cell wall fractions of the SrtA<sup>−</sup> strain, possibly due to the copurification of membrane-tethered pili with cell wall materials for unknown reasons. However, we cannot rule out the possibility that SrtC or some other factor anchors pili to the cell wall in the absence of SrtA, as seen for *S. pneumoniae* pili encoded by the *ihA* island.

Interestingly, while in *C. diphtheriae* the phenotypes of mutants lacking SrtF and its substrate anchor pilin SpaB are similar, the phenotypes of the *E. faecalis* OG1RF SrtA<sup>−</sup> and EbpB<sup>−</sup> strains are discordant. In contrast to the SrtA<sup>−</sup> strain, no accumulation of pili in bacterial cell membranes was observed in the EbpB<sup>−</sup> strain (data not shown). It is possible that pili in the EbpB<sup>−</sup> strain may be anchored to the cell wall by processing of EbpC by SrtA or SrtC. In that case, the signal for termination of pilus polymerization by SrtC is unclear. Alternatively, membrane-accumulated pili may simply be undetectable in the EbpB<sup>−</sup> strain due to the reduction in pilination previously reported for this strain (10). In contrast, we show here that expression of pili in the SrtA<sup>−</sup> strain was increased.

Detailed study of sortase-assembled pilus biogenesis began with pioneering work with the *C. diphtheriae* and *A. naeslundii* pilus islands and has now continued in the GAS, GBS, and *S. pneumoniae* pilus systems (6). Together, these studies show that some aspects of pilus biogenesis, such as a dedicated subunit and sortase(s) for fiber polymerization, are universal, while others, such as the importance of the housekeeping sortase in cell wall-anchoring, may vary among systems. In the rational development of small molecule therapeutics for Gram-positive infections that target sortase activity and sortase-assembled pilus assembly, it will be critical to understand how sortase activity and pilus biogenesis differ among bacterial species. We present here the first detailed study of the molecular determinants of pilus biogenesis in *E. faecalis*, an increasingly important human pathogen.

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