PspA Protects *Streptococcus pneumoniae* from Killing by Apolactoferrin, and Antibody to PspA Enhances Killing of Pneumococci by Apolactoferrin

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Lactoferrin is an important component of innate immunity through its sequestration of iron, bactericidal activity, and immune modulatory activity. Apolactoferrin (ALF) is the iron-depleted form of lactoferrin and is bactericidal against pneumococci and several other species of bacteria. We observed that lactoferrin (LFN), an 11-amino-acid peptide from the N terminus of lactoferrin, is bactericidal for *Streptococcus pneumoniae*. Strains of *S. pneumoniae* varied in their susceptibility to ALF. Lactoferrin is bound to the pneumococcal surface by pneumococcal surface protein A (PspA). Using mutant PspA⁺ pneumococci of four different strains, we observed that PspA offers significant protection against killing by ALF. Knockout mutations in genes for two other choline-binding proteins (PspC and PcpA) did not affect killing by ALF. PspA did not have to be attached to the bacterial surface to inhibit killing, because the soluble recombinant N-terminal half of PspA could prevent killing by both ALF and LFN. An 11-amino-acid fragment of PspA was also able to reduce the killing by LFN. Antibody to PspA enhanced killing by lactoferrin. These findings suggested that the binding of ALF to PspA probably blocks the active site(s) of ALF that is responsible for killing.

*Streptococcus pneumoniae* is a major cause of pneumonia, meningitis, septicaemia, and otitis media (20, 21, 41), and causes about 50,000 fatalities annually in the United States (22). Globally, pneumococci kill at least 1 million children every year (21, 47, 60). Asymptomatic human nasopharyngeal carriage is the major reservoir of pneumococci. Carriage can last from weeks to months and can be found in 40% or more of young children but is found in a lower percentage of adults (3, 49). Acquisition of carriage is generally from carriers of *S. pneumoniae*, with disease occurring in a subset of newly colonized individuals through invasion of the blood, middle ear, lung, and/or brain (32). Host immunity that minimizes colonization should reduce pneumococcal disease and the spread of pneumococci within the community.

A 7-valent vaccine containing capsular polysaccharides conjugated to a nontoxic variant of diphtheria toxin has successfully reduced invasive infections caused by pneumococci expressing the seven capsular types included in the vaccine (9, 53). The vaccine has been less successful at eliciting protection against carriage, partially because of a postvaccination increase in the rate of carriage of capsular types not present in the vaccine (27, 28). Several pneumococcal proteins have been examined in animals for their ability to serve as pneumococcal vaccines (15). One of these, pneumococcal surface protein A (PspA), is important for full virulence in invasive pneumococcal infections in mice (8, 16, 44). Immunization with PspA elicits protection in mice against invasive infection (13, 14, 61, 62) as well as nasal carriage (10, 13, 14, 61, 62). PspA has successfully undergone a limited human safety trial (12, 45). The human antibodies to PspA elicited during this safety trial were able to protect mice from otherwise fatal pneumococcal sepsis (12, 45). The PspA protein and/or the *pspA* gene have been shown to be present in all of the over 2,000 clinical isolates of deoxycholate-soluble pneumococci for which capsular types could be identified (25, 26, 38; S. K. Hollingshead, unpublished data). PspAs are divided into two major families based on their immunologic cross-reactivity and sequence diversity (25, 38).

In invasive infections, PspA’s role in virulence is thought to be due to its ability to inhibit complement deposition (46, 51, 56). In invasive infections, PspA must be attached to the pneumococcal surface for it to affect virulence. Strains with mutations that result in the secretion of PspA are as avirulent as those making no PspA (51, 66). PspA may have a different role in nasal carriage. A recent study established carriage in human volunteers by using a pneumococcal strain that secreted the N-terminal half of PspA and that did not express surface PspA. Preexisting antibody to PspA appeared to prevent carriage (42). These findings suggested that, in human carriage, PspA is a colonization factor and need not be surface attached. Thus, PspA might act by a very different mechanism in mucosal carriage, where complement concentrations are very low, than in invasive disease, where complement-dependent opsonophagocytosis is critical to protection (19, 50, 56).

A possible explanation for PspA’s role in carriage is suggested by its ability to bind lactoferrin (33, 34). Surface binding of lactoferrin to live pneumococci is dependent on PspA (33). Lactoferrin is present in significant quantities (1 to 14 mg/ml) in milk, saliva, and tears and is thought to offer protection against nasal colonization and infection by some bacteria (2, 31, 59). Lactoferrin is a 78-kDa single-chain glycoprotein folded into an N-lobe and a C-lobe. Each lobe contains one iron-binding site. Hololactoferrin (HLF) has one bound metal ion...
cocc i were scraped from the plate and used to inoculate THY broth. Cultures were incubated on a candle jar on blood agar overnight at 37°C. Pneumococci were obtained as frozen cultures (−80°C) in Todd-Hewitt Broth containing 0.5% yeast extract (THY) with 10% glycerol. The strains shown in Table 1 include the wild-type parents and their isogenic mutants. Our investigators have described an iron chelating ability, which can deplete iron and restrict bacterial growth (48). ALF is also bactericidal against a wide range of bacteria, including Escherichia coli, Vibrio cholerae, Streptococcus mutans, and S. pneumoniae (4, 24, 58). The bactericidal activity of ALF is associated with the N-terminal 47 amino acids of the protein, which is part of the N-lobe (55). Bactericidal peptides from this region are collectively termed lactoferricins (LFNs); peptides as small as 11 amino acids are highly bactericidal against a wide range of bacteria, including S. pneumoniae, and Staphylococcus spp. (4, 24, 58). The bactericidal activity of ALF is due in part to its killing of pneumococci by ALF. We have investigated the possibility that PspA protects pneumococci from killing by ALF and that antibody to PspA may prevent binding of PspA to ALF and thus facilitate killing of pneumococci by ALF.

**Materials and Methods**

**Bacterial strains and growth conditions.** Strains of S. pneumoniae were maintained as frozen cultures (−80°C) in Todd-Hewitt Broth containing 0.5% yeast extract (THY) with 10% glycerol. The strains shown in Table 1 include the wild-type parents and their isogenic mutants. Our investigators have described strains EF6796, DBL6A, DBL1, LS2016, and EF10197 previously (11); strains EF6796, DBL6A, DBL1, L82016, and EF10197 were obtained from Minjun Chen, University of Alabama at Birmingham; and MF-V178 strains EF6796, DBL6A, DBL1, L82016, and EF10197 previously (11); strains wild-type parents and their isogenic mutants. Our investigators have described expression of Ps.pA by ALF. We have investigated the possibility that PspA protects pneumococci from killing by ALF and that antibody to PspA may prevent binding of PspA to ALF and thus facilitate killing of pneumococci by ALF.

**TABLE 1. Parental and mutant S. pneumoniae strains used in these studies**

<table>
<thead>
<tr>
<th>Strain</th>
<th>Capsule type</th>
<th>PspA family/clade</th>
<th>Genetic background</th>
<th>Phenotype*</th>
<th>Size (kDa) of expressed PspA</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td>WU2</td>
<td>3</td>
<td>1/2</td>
<td>WU2</td>
<td>PspA*</td>
<td>73</td>
<td>65</td>
</tr>
<tr>
<td>JY1119</td>
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<td>1/2</td>
<td>WU2</td>
<td>PspA*</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
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<td>2</td>
<td>1/2</td>
<td>D39</td>
<td>PspA*</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>JY182</td>
<td>2</td>
<td>1/2</td>
<td>D39</td>
<td>PspA*</td>
<td>65</td>
<td>65</td>
</tr>
<tr>
<td>KM004</td>
<td>2</td>
<td>1/2</td>
<td>D39</td>
<td>PspA**</td>
<td>43</td>
<td>44</td>
</tr>
<tr>
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<td>2</td>
<td>1/2</td>
<td>D39</td>
<td>PspC-**</td>
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<td>18</td>
</tr>
<tr>
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<td>PspA*</td>
<td>82</td>
<td>38</td>
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<tr>
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<td>51</td>
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<td>38</td>
</tr>
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<td>1/1</td>
<td>EF3030</td>
<td>PspA*</td>
<td>43</td>
<td>7</td>
</tr>
</tbody>
</table>

* tr, truncated by deletion of C-terminal sequence. **, strain where the theoretical expressed product was 1 to 2.5 kDa was scored as a negative phenotype.

modified from an earlier solution of Arnold et al. (6). Bacteria were suspended to a concentration of approximately 10^5 CFU (OD_{600} = 0.1 to 0.2, or 2 x 10^7 CFU/ml). Isogenic mutants lacking expression of intact PspA, pneumococcal surface protein C (PspC), or pneumococcal choline-binding protein A (PspA) were grown in the presence of appropriate antibiotics.

**Construction of PspA**∗ strain. A PspA**−** strain was constructed in the D39 genetic background by using insertion-duplication mutagenesis. A 300-bp DNA fragment was amplified using primers JW28 (5′-AAGCTTTGACAGTTGTAATGG-3′) and JW29 (5′-TGAACCTTGGAGAAAAGGTGAC-3′) corresponding to bp 2276 to 2296 and 2687 to 2686 of pscp of the TIGR4 sequence (accession number NC003028). The amplified PCR product was cloned into the pTOPO cloning vector (Invitrogen, Carlsbad, Calif.) according to the manufacturer’s instructions. The insert from the pTOPO plasmid was digested with BamHI and PstI, ligated into pYJ4164, and digested with BamHI and PstI. Plasmid pYJ4164 contains an erythromycin-resistant marker (1) pcpA mutant strain KM004 was generated by transforming S. pneumoniae strain D39 with pYJ4164 containing the 300-bp fragment of the pcpA plasmid as described by Yother et al. with the following modifications: competence factor was synthetically synthesized and was obtained from Zymed Laboratories (San Francisco, Calif.) (37). Cultures were induced with 500 ng of competence factor/ml and incubated at 37°C for 12 min before addition of plasmid DNA. Transformants were plated on erythromycin plates (0.3 µg/ml) and resistant colonies were screened for inserts. The integration of an insert into the chromosome was determined by the PCR amplification of the insert using primer JW30 (5′-CC TTTACATGTGTTTTTGG-3′), which binds upstream of the plasmid integration site (bp 1714 and 1735), and primer TTI (5′-GCCACTATCGACTACGCG-3′), which is specific for the plasmid pYJ4164. The presence of an expected 973-bp band in the PCR product confirmed the integration of the plasmid in the expected position of the D39 chromosome.

**Treatment of S. pneumoniae with ALF and HLF.** Human ALF (L0520) and HLF (L3770) were purchased from Sigma Chemical (St. Louis, Mo.). The individual lots were 87 to 95% pure, with the bulk of the non lactoferrin molecules being immunoglobulin A. ALF lots were supplied containing from 0.01 to 0.06% iron. HLF was supplied at 0.1 to 0.2), washed, and resuspended in assay solution (AS; being immunoglobulin A. ALF lots were supplied containing from 0.01 to 0.06% iron. HLF was supplied at 0.1 to 0.2), washed, and resuspended in assay solution (AS; or Fe^3+). The bactericidal activity of ALF is due in part to its killing of pneumococci by ALF and that antibody to PspA may prevent binding of PspA to ALF and thus facilitate killing of pneumococci by ALF.
Treatment of bacteria with LFN. Two LFN peptides, LFN1 (GRRRRSVO WCA [amino acids 1 to 11 of human ALF]) and LFN2 (FOWQRMRKVR [amino acids 21 to 31]) (Research Genetics, Invitrogen, Huntsville, Ala.), were tested for their ability to kill strains D39 and JY182 (PspA− D39) in AS at the concentrations indicated.

Effect of lactoferrin on S. pneumoniae. We examined the effects of ALF and HLF on the viability of S. pneumoniae in AS. The two proteins were added separately to tubes of S. pneumoniae strain D39 (capsular type 2, PspA family one) at a concentration of 3.1 μM (250 μg/ml). Treatment with ALF, but not HLF, resulted in a decline in the number of CFU (Fig. 1A). Most likely not all the bacteria were killed by 1 h at 37°C, each bar represents the log_{10} CFU. (B) Effect of converting ALF to HLF by treatment with 6% ferrous ammonium sulfate (followed by dialysis in water to remove excess iron). Each bar represents the mean log of six replicates from two independent experiments. The presence of ALF resulted in a significant (* *) decline in viability (P = 0.007), whereas saturation of ALF with ferrous ammonium sulfate resulted in inhibition of the bactericidal effects of ALF (P < 0.0001). In this figure and all subsequent figures, the error bars represent the standard errors of means.

RESULTS

Effect of lactoferrin on S. pneumoniae. We examined the effects of ALF and HLF on the viability of S. pneumoniae in AS. The two proteins were added separately to tubes of S. pneumoniae strain D39 (capsular type 2, PspA family one) at a concentration of 3.1 μM (250 μg/ml). Treatment with ALF, but not HLF, in AS alone. Viability of cells was determined by plating aliquots on blood agar plates after 1 h at 37°C, each bar represents the log_{10} CFU. (B) Effect of converting ALF to HLF by treatment with 6% ferrous ammonium sulfate (followed by dialysis in water to remove excess iron). Each bar represents the mean log of six replicates from two independent experiments. The presence of ALF resulted in a significant (* *) decline in viability (P = 0.007), whereas saturation of ALF with ferrous ammonium sulfate resulted in inhibition of the bactericidal effects of ALF (P < 0.0001). In this figure and all subsequent figures, the error bars represent the standard errors of means.
types 2, 3, 4, and 19F) and their PspA/H11002 isogenic mutants for susceptibility to killing by ALF. In each case, more killing was observed for the PspA/H11002 than PspA/H11001 strains (Fig. 4). For each pair of strains, the differences in killing between the PspA/H11002 and PspA/H11001 strains increased as the ALF concentration increased. One of these three strains, WU2, exhibited such a high innate resistance to killing that even the PspA/H11002 strain showed no evidence of being killed in this experiment until the ALF concentration reached 3.1 \( \mu \)M (250 \( \mu \)g/ml). The PspA/H11002 mutants of strains D39, WU2, and TIGR4 secreted no PspA.

For strains D39 and WU2, we also had variants that either expressed no PspA or expressed an N-terminal fragment of their PspA that was secreted into the medium and therefore was no longer attached to the surface (65). In each case, the strains making surface PspA and those secreting fragments of PspA were more resistant to killing than those making no PspA (Fig. 5). The D39 strain making the truncated PspA showed intermediate resistance to killing by ALF. The WU2 strain making truncated PspA resulted in as much protection against ALF as was afforded by making the whole molecule.

The susceptibility of the PspA\(^-\) strain was also evaluated over several time points ranging from 30 to 120 min, with 1.25 \( \mu \)M ALF. This dose of ALF was the lowest that gave significant killing against these strains. By 30 min there was 0.75 log more killing of PspA\(^-\) than PspA\(^+\) D39, and this difference did not change with increasing time. For EF3030, significantly (\( P < 0.05 \)) greater killing of the PspA\(^-\) pneumococci (0.75 to 0.80 log killing) was not observed until 60 min, and the difference was still increasing at 120 min (data not shown).

Although the kinetics of killing (preceding paragraph) and the amount of ALF required to kill (Fig. 4 and 5) differed for

![Image](http://iai.asm.org/ on August 15, 2017 by guest)
different strains, in all cases the expression of PspA was able to reduce killing by ALF. These data make a robust case for PspA being able to inhibit the ability of ALF to kill pneumococci. The results also demonstrate that PspA need not be surface attached to be able to protect pneumococci against killing by added ALF.

**Bactericidal effects of ALF on PspC<sup>-</sup> and PcpA<sup>-</sup> S. pneumoniae mutants.** To test the specificity of the effects of the pspA mutations on killing by 3.1 μM ALF, we also examined mutants of D39 unable to make PspC or PcpA. Mature PspC and PcpA of strain D39 are 90- and 79-kDa surface choline-binding proteins (18, 52), but neither contributes to the surface binding of lactoferrin because PspA<sup>-</sup> pneumococci, which still make PspC and PcpA, do not bind lactoferrin (33). The PspC and PcpA mutants made truncated N-terminal 2.2- and 1.0-kDa proteins. In this study the PspA<sup>-</sup> strain showed 1.8 log of killing compared with 1 log of killing for the PspA<sup>+</sup> strain over 1 h of incubation at 37°C. Neither the pspC nor pcpA mutants resulted in an increase in susceptibility to killing by ALF (data not shown). These data made it clear that the insertion-duplication mutation process in itself does not affect resistance to killing by ALF and that the surface expression of PspC and PcpA is not necessary for protection against killing by ALF.

**Recombinant PspA inhibits the bactericidal effects of ALF.** To test the possibility that cell-free PspA could interfere with killing by ALF, we examined the ability of a rPspA, UAB055,
to prevent killing by ALF. UAB055 comprises the N-terminal 302 amino acids of the mature PspA from strain D39 (39). This fragment is therefore inclusive of the region of PspA (amino acids 192 to 288) within which the binding site of lactoferrin has been mapped (33). These studies were conducted using viable D39 and its PspA/H11002 variant, JY182, as a target strain. In each case, 0.2 μM rPspA was able to cause complete protection against killing by a 15-fold excess (3.1 μM) of ALF (Fig. 6). As controls, we added 3.1 μM human albumin or 1.16 μM rPsaA. Neither of these molecules inhibited killing by ALF (data not shown). The ability of PspA to readily prevent killing by ALF, whether the PspA was bound to the cell surface or in solution, suggests that the PspA may be blocking ALF-mediated killing by neutralizing the site(s) on lactoferrin responsible for the killing. The ability of rPspA to inhibit killing by an excess of ALF suggests that one PspA may bind and inactivate more than one ALF. An alternative, more speculative, explanation might be that the rPspA somehow “catalyzes” a conformational transformation in ALF that prevents it from being able to kill.

**Bactericidal effects of LFN1 and LFN2.** The peptides LFN1, GRRRRSVQWCA (amino acids 1 to 11 of human ALF), and LFN2, FQWQRNMRKVR (amino acids 21 to 31), were able to kill strain D39. Two micromolar concentrations each of LFN1 and LFN2 could cause about 2 logs of killing in AS after a 60-min incubation. This was significantly more killing than was observed with 3.1 μM ALF (Fig. 7).

**rPspA and its peptide SM1 block the activity of LFN1.** SM1, a 10-amino-acid peptide of Rx1 PspA (amino acids 269 to 278), encodes a sequence highly conserved among family 1 and family 2 PspAs (38) within amino acids 193 to 288 in the N-terminal half of PspA, where lactoferrin is known to bind (33).

![FIG. 6. Inhibition of bactericidal activity of ALF in the presence of soluble 43-kDa rPspA from strain Rx1 for 1 h at 37°C. S. pneumoniae strain D39 (A) and its isogenic PspA H11002 mutant JY182 (B) were incubated with AS, ALF, or ALF in the presence of rPspA for 1 h. **, the viability of the pneumococci was significantly (P = 0.002) different from viability of pneumococci treated with ALF but no rPspA. Data shown are from three independent experiments, and each bar represents the mean log and standard error of a total of 12 replicates.](https://iai.asm.org/article-pdf/64/12/5036/4009951/64_5036_Shafer.pdf)

![FIG. 7. Bactericidal activity of ALF and two LFN molecules compared with that of ALF, LFNs and ALF were incubated with strain D39 at the indicated concentrations in AS. All treatments with ALF, LFN1, or LFN2 caused significant decreases in viability compared with the diluent control (**, P < 0.0023). Treatment with 3.1 μM ALF was less effective than treatment with 2 μM LFN1 or either 1 or 2 μM LFN2 (**, P < 0.0023). Data presented here represent the mean log and standard error of 12 replicates performed in two independent experiments.](https://iai.asm.org/article-pdf/64/12/5036/4009951/64_5036_Shafer.pdf)
Using 1 μM SM1, we were able to significantly reduce (1 log₁₀) the killing of PspA⁻ strain D39 pneumococci caused by 1 μM LFN1. Similar results were obtained when PspA⁻ strain D39 was treated with LFN1 in the presence of SM1 (Fig. 8). SM1 was not, however, able to inhibit killing by ALF (data not shown). The sequence of SM1 was present only once in PspA and does not occur in PspC or PcpA. Another peptide encoding Rx1 amino acids 230 to 244 (SM2) was not protective against ALF (data not shown).

### Ability of antibody to PspA to facilitate killing of a strain of PspA⁻ pneumococci with ALF.

If PspA blocks killing of pneumococci by binding to ALF, then it would be expected that antibody to PspA might prevent binding of ALF to PspA and thereby enhance the killing of pneumococci by ALF. In this study we observed that ALF was causing almost 1 log of killing of D39 pneumococci. If the pneumococci were incubated with a 1/100 dilution of a rabbit antiserum to PspA prior to the addition of ALF, about 2.5 logs of killing were observed (Fig. 9). Thus, the antibody to PspA enhanced the killing by ALF by 1.5 logs. As controls we used (also at 1/100 dilution) a rabbit antiserum to PspC from strain D39 (18), preimmune rabbit sera from the PspA-immune rabbit, and normal mouse serum; none of these enhanced killing by ALF (data not shown).

### Treatment with ALF in the presence of saliva.

As lactoferrin is an antibacterial protein found in many human secretions, it was important to determine if it is bactericidal in that environment. Early log-phase D39 pneumococci were incubated in two fresh samples of human saliva. In one sample the pneumococci were killed so quickly that it was not possible to study the effects of added ALF. In the other sample we incubated D39 in the saliva for 1 h at 37°C with and without added ALF. At 3.1 μM ALF, we observed 1.3 logs of killing. At 6.2 μM ALF, we observed 2.1 logs of killing (data not shown).

### DISCUSSION

The data in this paper confirm and extend the earlier observation (40) that ALF has bactericidal activity against S. pneumoniæ.
moniae. In contrast, HLF was not found to have an effect on pneumococcal viability. PspA has been shown to be the attachment site for lactoferrin binding to the pneumococcal surface (33, 34). In the present paper we have shown that the attachment of ALF to PspA is not necessary for ALF to kill pneumococci. In fact, the killing of pneumococci by ALF is much more efficient if PspA is absent. The effects of mutations in pspA on ALF-mediated killing were specific: the disruption of genes for two other choline-binding surface proteins (pspC and pcpA) failed to show any effect on the bactericidal activity of ALF.

The observations that (i) ALF can kill pneumococci, (ii) virtually all lactoferrin surface binding to pneumococci is via PspA, and (iii) PspA prevents killing by ALF argue that an important role of PspA in the natural history of pneumococcal carriage and/or infections is to prevent this killing of pneumococci by ALF. Our observation that added ALF can kill pneumococci suspended in human saliva strongly supports these conclusions. The demonstration that antibody to PspA can enhance killing of pneumococci by ALF strongly suggests that antibody to PspA may be able to protect against pneumococcal colonization and possibly also against infection.

The relationship between lactoferrin binding and pathogenesis is different for pneumococci than for some other bacteria where binding to ALF has been shown to be a prerequisite for its bactericidal effects. The differences in sensitivity of Micrococcus luteus strains to killing by ALF are attributed to the differential binding of ALF to surface proteins of M. luteus (29). In the case of pneumococci, the ALF that binds to PspA appears to be blocked from being able to kill pneumococci.

The ability of cell-free PspA to block ALF-mediated killing indicates that PspA may block killing by binding the active killing site(s) on ALF. Our observation that the molar concentration of rPspA required to block ALF-mediated killing could be less than the concentration of ALF indicates that one PspA molecule can bind and inhibit more than one ALF molecule.

Both of the LFN peptides, LFN1 and LFN2, were also able to kill pneumococci. This suggests that the mechanism that ALF uses to kill pneumococci is probably membrane destabilization similar to that caused by other antibacterial cationic peptides rich in tryptophans (35). The killing activity of LFN1 was strongly inhibited by rPspA and was inhibited almost as well by SM1, a 10-amino-acid peptide of PspA. SM1 is highly conserved in PspA clades 1 to 5, which contain all the PspA sequences in the two major PspA families (38). SM1 is also the only conserved region within the region of Rx1 PspA previously shown to bind lactoferrin (33).

The ability of SM1 to inhibit killing by LFN indicates that the region of PspA that includes SM1 may be particularly important in blocking killing by LFN and possibly by ALF as well. It is also possible that rPspA binds LFN1 at more sites than just SM1. SM1’s inability to inhibit killing by ALF may also be an indication that ALF has sites involved in killing that are not recognized by SM1. It is also possible that SM1 is not in exactly the same configuration as the corresponding amino acids in the complete PspA molecule. Our findings also raise the possibility that differences in the PspA expressed, or in the amounts of PspA expressed, may explain some of the variability in susceptibility of different pneumococci to killing by ALF.

Based on the results presented here, it is clear that PspA can prevent killing by ALF regardless of whether it is secreted or surface attached. We have also shown that antibody to PspA can enhance killing by ALF, presumably by preventing ALF from being bound by PspA. Thus, our findings suggest a mechanism by which antibody to PspA in airway secretions might prevent or reduce carriage of pneumococci and offer an explanation to help explain data in the mouse showing that mucosal immunity to PspA can reduce colonization (10, 61).

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ERRATUM

PspA Protects Streptococcus pneumoniae from Killing by Apolactoferrin, and Antibody to PspA Enhances Killing of Pneumococci by Apolactoferrin

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