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Helicobacter pylori SabA Adhesin in Persistent Infection and Chronic Inflammation

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Helicobacter pylori adherence in the human gastric mucosa involves specific bacterial adhesins and cognate host receptors. Here, we identify sialyl-dimeric-Lewis x glycosphingolipid as a receptor for H. pylori and show that H. pylori infection induced formation of sialyl-Lewis x antigens in gastric epithelium in humans and in a Rhesus monkey. The corresponding sialic acid—binding adhesin (SabA) was isolated with the "retagging" method, and the underlying sabA gene (JHP662/HP0725) was identified. The ability of many H. pylori strains to adhere to sialylated glycoconjugates expressed during chronic inflammation might thus contribute to virulence and the extraordinary chronicity of H. pylori infection.

Leb antigen—indeed binding. Earlier studies identified nearly identical babA genes at different H. pylori chromosomal loci, each potentially encoding BabA. The babA2 gene encodes the complete adhesin, whereas babA1 is defective because sequences encoding the translational start and signal peptide are missing (4). Our experiments began with analyses of a babA2-knockout mutant derivative of the reference strain CCUG17875 (hereafter referred to as 17875). Unexpectedly, this 17875 babA2 mutant bound to gastric mucosa from an H. pylori—infected patient with gastritis.

A 17875 derivative with both babA genes inactivated (babA1A2) was constructed (14). This babA1A2 mutant also adhered (Fig. 1, B and C), which showed that adherence was not due to recombination to link the silent babA1 gene with a functional translational start and signal sequence. Pretreatment with soluble Leb antigen (structures in table S1) resulted in >80% lower adherence by the 17875 parent strain (Figs. 1E and 3C) but did not affect adherence by its babA1A2 derivative (Figs. 1F and 3C).

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In contrast to binding to infected gastric mucosa (Fig. 1, A to I), the babA1A2 mutant did not bind to healthy gastric mucosa from a person not infected with H. pylori (Fig. 1, J to M), whereas the 17875 parent strain bound avidly (Fig. 1, M versus L). These results implicated another adhesin that recognizes a receptor distinct from the Leb antigen and possibly associated with mucosal inflammation.

Adherence was also studied in tissue from a special transgenic mouse that produces Leb antigen in the gastric mucosa, the consequence of expression of a human-derived α1,3/4 fucosyltransferase (FT) (15). Strain 17875 and the babA1A2 mutant each adhered to Leb mouse gastric epithelium (Fig. 2A, ii and iii), whereas binding of each strain to the mucosa of nontransgenic (FVB/N) mice was poor and was limited to the luminal mucus. Thus, Leb mice express additional oligosaccharide chains (glycans), possibly fucosylated, but distinct from the Leb antigen that could exploit as a receptor.

sdilex antigen-mediated binding. To search for another receptor, thin-layer chromatography (TLC)—separated glycosphingolipids (GSLs) were overlaid with H. pylori cells and monoclonal antibodies (mAbs), as appropriate. These tests (i) showed that the babA1A2 mutant bound acid GSLs (Fig. 2B, iv, lanes 2 and 4), (ii) confirmed that it did not bind Leb GSL (lane 9), (iii) showed that its binding was abrogated by desialylation (lanes 3 and 5), and (iv) revealed that it did not bind sialylated GSLs of nonhuman origin (lane 1) (table S1, numbers 2 to 5, in (16)) (indicating that sialylation per se is not sufficient for...
adherence). In addition, the binding pattern of the babA1A2 mutant matched that of the mAb against sLex (Fig. 2B, ii versus iv), except that sLex-mono-GSL was bound more weakly by the babA1A2 mutant than by the mAb (Fig. 2B, iv) and no binding to sialyl-Lewis a-GSL was detected (table S1). Thus, the babA1A2 mutant preferably binds sialylated gangliosides, possibly with multiple Lex (fucose-containing) motifs in the core chain (thus, slower migration on TLC).

The babA1A2-mutant strain was next used to purify a high-affinity binding GSL from human adenocarcinoma tissue (14). The H. pylori–binding GSL was identified by mass spectrometry and 1H nuclear magnetic resonance (NMR) as the sialyl-dimeric-Lewis x antigen, abbreviated as the sdiLex antigen (Fig. 2, B and C) (14).

Further tests with soluble glycoconjugates showed that the 17875-parent strain bound both sLex and Leb antigens, whereas its derivative bound only sLex (Fig. 3A). Pretreatment of the babA1A2 mutant with sLex conjugate reduced its in situ adherence by more than 90% (Figs. 1I and 3C) (14) but did not affect adherence of the 17875 parent strain (Figs. 1H and 3C). Similarly, pretreatment of tissue sections with an mAb that recognizes sdiLex reduced adherence by the babA1A2 mutant by 72% (Fig. 3E).

Titration experiments showed that the babA1A2 mutant exhibited high affinity for the sdiLex GSLs, with a level of detection of 1 pmol (Fig. 2B, iv) (table S1, number 8). At least 2000-fold more (2 nmol) of the shorter sialyl-(mono)-Lewis x GSL was needed for binding (table S1, number 7). In contrast, its affinity (Kd) for soluble conjugates was similar for mono and dimeric forms of sLex, 1 × 10−7 M−1 and 2 × 10−7 M−1, respectively (Fig. 3B) (16). These patterns suggest that the sialylated binding sites are best presented at the termini of extended core chains containing multiple Lewis x motifs, such as GSLs in cell membranes. Such optimization of steric presentation would be less important for soluble receptors.

The Scatchard analyses (16) also estimated that 700 sLex-conjugate molecules were bound per babA1A2-mutant bacterial cell (Fig. 3B), a number similar to that of Leb conjugates bound per cell of strain 17875.

Clinical isolates. A panel of 95 European clinical isolates was analyzed for sLex binding (14). Thirty-three of the 77 cagA+ strains (43%) bound sLex, but only 11% (2 out of 18) of cagA− strains (P < 0.000). However, deletion of the cagPAI from strain G27 did not affect sLex binding, as had also been seen in studies of cagA− strains (14). No staining was detected with the sLex mAb (Fig. 3B, i) but did not affect adherence of the babA1A2 mutant (Fig. 3B, iv). BabA1A2-mutant binding in situ and in gastric biopsies from 29 endoscopy patients of the babA1A2 mutant and by the 17875 strain in situ, and for several markers of inflammation (table S2A) (14). Substantial correlations were found between babA1A2-mutant adherence and the following parameters: (i) levels of neutrophil (PMN) infiltration, 0.47 (P < 0.011); (ii) lymphocyte/plasma cell infiltration, 0.46 (P < 0.012); and (iii) mAb staining for sLex in surface epithelial cells and in gastric pit regions, 0.52 (P < 0.004); and (iv) histological gastritis score, 0.40 (P < 0.034). In contrast, there was no significant correlation between babA1A2-mutant binding in situ and H. pylori density in biopsies from natural infection (0.14, P < 0.47), nor between any inflammatory parameter and in situ adherence of strain 17875 (Leb and sLex binding).

Fig. 1. The sLex antigen confers adherence of H. pylori to the epithelium of H. pylori–infected (strain WU12) human gastric mucosa (Fig. 3A). H/E staining reveals mucosal inflammation (A). The 17875 parent strain (B) and the babA1A2 mutant (C) both adhere to the gastric epithelium. The surface epithelium stains positive (arrows) with both the Leb mAb (D) and slex mAb (G) [AIS described in (14)]. The 17875 strain and babA1A2 mutant responded differently after pretreatment (inhibition) with soluble Leb antigen [(E) and (F), respectively], or with soluble sLex antigen [(H) and (I), respectively]. In conclusion, the Leb antigen blocked binding of the 17875 strain, whereas the sLex antigen blocked binding of the babA1A2 mutant. H/E-stained biopsy with no H. pylori infection (J). No staining was detected with the sLex mAb (K). Here, strain 17875 adhered (L), in contrast to the babA1A2 mutant (M), because noninflamed gastric mucosa is low in sialylation (K).
The series of 29 patient biopsies was then compared to a series of six biopsies of *H. pylori*-infected individuals, and a considerable difference was found to be due to lower adherence of the babA1A2 mutant (P < 0.0001) (table S2B), whereas strain 17875 showed no difference.

**Binding to infected tissue.** Biopsy material from a Rhesus monkey was used to directly test the view that *H. pylori* infection stimulates expression of sialylated epithelial glycosylation patterns that can then be exploited by *H. pylori* for adherence [monkey biopsies in (14)]. This monkey (21) had been cleared of its natural *H. pylori* infection, and gastritis declined to baseline. Gastric biopsies taken at 6 months post-eradication showed expression of sLex in the gastric gland region (Fig. 4A) and no expression in the surface epithelium (Fig. 4A). In situ adherence of the babA1A2 mutant was limited to gastric glands and was closely matched to the sLex expression pattern (Fig. 4B). No specific adherence to the surface epithelium was seen (Fig. 4B).

At 6 months post-therapy, this gastritis-free animal had been experimentally infected with a cocktail of *H. pylori* strains, of which the J166 strain (a cagA-positive, Leb and sLex binding isolate) became predominant a few months later. This led to inflammation, infiltration by lymphocytes [Fig. 4C, bluish due to hematoxylineosine (H/E)–staining], and microscopic detection of *H. pylori* infection (Fig. 4, E and F) (21). The virulent *H. pylori* infection led to strong sLex-antigen expression in the surface epithelium (Fig. 4C) and maintained expression in the deeper gastric glands (Fig. 4C); thus, a bi-layered expression mode supported strong binding of the babA1A2 mutant to both regions (Fig. 4D). Bacterial pretreatment with sLex conjugate eliminated surface epithelial adherence and reduced gastric gland adherence by 88%. Thus, persistent *H. pylori* infection upregulates expression of sLex antigens, which *H. pylori* can exploit for adherence to the surface epithelium.

**Binding to Leb transgenic mouse gastric epithelium.** We analyzed gastric mucosa of Leb mice for sLex antigen-dependent *H. pylori* adherence in situ [AIS, in (14)]. Pretreatment with the sLex conjugate reduced binding by babA1A2-mutant bacteria by more than 90% (Figs. 2A, vi, and 3D) but did not affect binding by its 17875 parent (Figs. 2A, v, and 3D). In comparison, pretreatment with soluble Leb antigen decreased adherence by >80% of the 17875 strain (Leb and sLex binding), whereas binding by the babA1A2 mutant was not affected. mAb tests demonstrated sLex antigen in the gastric surface epithelium and pits of Leb mice (Fig. 2A, iv). That is, these mice are unusual in producing sialyl as well as Leb glycoconjugates (even without infection), which each serve as receptors for *H. pylori*.

A finding that *H. pylori* pretreatment with Leb conjugate blocked its adherence to Leb mouse tissue, whereas sLex pretreatment did not, had been interpreted as indicating that *H. pylori* adherence is mediated solely by Leb antigen (22). However, because strain 17875 and its babA1A2 mutant bound similar levels of soluble sLex conjugate (Fig. 3A), soluble Leb seems to interfere sterically with interactions between sLex-specific *H. pylori* adhesins and sLex receptors in host tissue (see also Fig. 1, E versus F). Because an excess of soluble sLex did not affect *H. pylori* binding to Leb receptors [Figs. 1H and 3C (in humans) and Figs. 2A, v, and 3D (in Leb-mice)], the steric hindrance is not reciprocal. Further tests showed that liquid phase binding is distinct. A 10-fold excess of soluble unlabeled Leb conjugate (3 μg) along with 300 ng of 125I-sLex conjugate did not affect strain 17875 binding to soluble sLex glycoconjugate. Soluble Leb conjugates interfere with sLex-mediated *H. pylori* binding specifically when the sLex moieties are constrained on surfaces. The lack of reciprocity in these Leb-sLex interference interactions contributes to our model of receptor positioning on cell surfaces.

**SabA identified.** We identified the sLex-binding adhesin by "retagging." This technique exploits a receptor-bound multifunctional biotinylated crosslinker, and ultraviolet (UV) irradiation to mediate transfer of the biotin tag to the bound adhesin (4). Here, we added the crosslinker to sLex conjugate and used more UV exposure (14) than had been used to isolate the BabA adhesin (4) to compensate for the lower affinity of the sLex than the Leb-specific adhesin for cognate soluble receptors (Fig. 3B). Strain J99 was used, and a 66-kDa protein was recovered (Fig. 5A). Four peptides identified by mass spectrometry (MS)–matched peptides encoded by gene JHP662 in strain J99 (17) (gene HP0725 in strain 26695) (18). Two of the four peptides also matched those from the related gene JHP659 (HP0722) (86% protein level similarity to JHP662) (fig. S1). To critically test if JHP662 or JHP659 encodes SabA, we generated camR insertion alleles of each gene in strain J99. Using radiolabeled glycoconjugates, we found that both sLex and Leb glycoconjugates...
and sLea antigen-binding activity was abolished in the JHP662 (sabA) mutant, but not in the JHP659 (sabB) mutant. Thus, the SabA adhesin is encoded by JHP662 (HP0725). This gene encodes a 651-aa protein (70 kDa) and belongs to the large hop family of H. pylori outer membrane protein genes, including babA (17, 18). The sabA gene was then identified by PCR in six sLeb-binding and six non-sLex-binding Swedish isolates, which suggests that sabA is present in the majority of H. pylori isolates (14).

Parallel studies indicated that the sabA inactivation did not affect adherence mediated by the BabA adhesin (Fig. 5B, i) and that pretreatment of the J99 sabA mutant with soluble Leb antigen prevented its binding to gastric epithelium (Fig. 5B, ii). This implies that the SabA and BabA adhesins are organized and expressed as independent units. Nevertheless, Leb conjugate pretreatment of J99 (BabA+ and SabA−) might have interfered with sLex antigen–mediated adherence (see Fig. 1E). To determine if this was a steric effect of the bulky glycoconjugate on exposure of SabA adhesin, single babA and sabA mutants J99 derivatives were used to further analyze Leb and sLex adherence (Fig. 5C, i to iv). Both single mutants adhered to the in-flamed gastric epithelial samples, whereas the babAsabA (double) mutant was unable to bind this same tissue.

**Instability of sLex binding.** When screening for SabA mutants, we also analyzed single colony isolates from cultures of parent strain J99 (which binds both sLex and Leb antigens) (Fig. 3A), which indicated that 1% of colonies had spontaneously lost the ability to bind sLex. Similar results were obtained with strain 17875 (Fig. 3A) with an OFF (non-sLex-binding) variant called 17875/Leb. In contrast, each of several hundred isolates tested retained Leb antigen–binding capacity.

Upstream and within the start of the sabA gene are poly T/CT tracts that should be hotspots for ON/OFF frameshift regulation [see HP0725 in (18)], which might underlie the observed instability of sLex-binding activity. Both strains’ genome sequences, 26695 and J99, demonstrate CT repeats that suggest sabA to be out of frame (six and nine CTs, respectively) (17, 18). Four sLex-binding and four non–sLex-binding Swedish isolates, and in addition strain J99, were analyzed by PCR for CT repeats, and differences in length were found between strains. Ten CT repeats [as compared to nine in (17)] were
found in the sLex-binding 399 strain, which puts this ORF in frame, and could thus explain the ON bindings. These results further support the possibility for a flexible locus that confers ON/OFF binding properties (23).

**Dynamics of sialylation during health and disease.** Our analyses of *H. pylori* adherence provide insight into human responses to persistent infections, where gastritis and inflammation elicit appearance of sdiLex antigens and related sialylated carbohydrates in the stomach mucosa, which \(\text{sLex}^+\) (virulent) *H. pylori* strains by adaptive mechanisms exploit as receptors in concert with the higher affinity binding to Leb. These two adherence modes may each benefit *H. pylori* by improving access to nutrients leached from damaged host tissues, even while increasing the risk of bacterial damage by these same host defenses (Fig. 6). In the endothelial lining, sialylated Lewis-glycans serve as receptors for selectin cell adhesion proteins that help guide leukocyte migration and thus regulate strength of response to infection or injury (24). For complementary attachment, the neutrophils themselves also express sialylated Lewis glycans, and such neutrophil glycans allow binding and infection by human granulocytic erlichiosis (25). However, sialylated glycoconjugates are low in healthy gastric mucosa but are expressed during gastritis. This sialylation was correlated with the capacity for SabA-dependent, but not BabA-dependent, *H. pylori* binding in situ. Our separate tests on Rhesus monkeys for experimental *H. pylori* infection confirmed that gastric epithelial sialylation is induced by *H. pylori*. In accord with this, high levels of sialylated glycoconjugates have been found in *H. pylori*-infected persons, which decreased after eradication of infection and resolution of gastritis (26). Thus, a sialylated carbohydrate used to signal infection and inflammation and to guide defense responses can be co-opted by *H. pylori* as a receptor for intimate adherence.

High levels of sialylated glycoconjugates are associated with severe gastric disease, including dysplasia and cancer (27, 28). Sialylated glycoconjugates were similarly abundant in parietal cell–deficient mice (22). sLex was also present in the gastric mucosa of transgenic Leb mice (Fig. 2A). Whether this reflects a previously unrecognized pathology stemming from the abnormal (for mice) gastric synthesis of \(\text{sLex}^+\) or Leb antigen, or from fucosylation of already sialylated carbohydrates, is not known.

Persons with blood group O and “nonsecretor” phenotypes (lacking the ABO blood group–antigen synthesis in secretions such as saliva and milk) are relatively common (e.g., ~45 and ~15%, respectively, in Europe), and each group is at increased risk for peptic ulcer disease (29). The H1 and Leb antigens are abundant in the gastric mucosa of secretors (of blood group O) (6), but not in nonsecretors, where instead the sLex and sLea antigens are found (30). The blood group O–disease association was postulated to reflect the adherence of most \(\text{sLex}^+\) *H. pylori* strains to H1 and Leb antigens (3). We now suggest that *H. pylori* adherence to sialylated glycoconjugates contributes similarly to the increased risk of peptic ulcer disease in nonsecretor individuals.

**Adaptive and multistep-mediated attachment modes of *H. pylori*.** Our findings that the SabA adhesin mediates binding to the structurally related sialyl-Lewis a antigen (sLea, in table S1) is noteworthy because sLea is an established tumor antigen (31) and marker of gastric dysplasia (27), which may further illustrate *H. pylori* capacity to exploit a full range of host responses to epithelial damage. The *H. pylori* BabA adhesin binds Leb antigen on glycoproteins (32), whereas its SabA adhesin binds sLex antigen in membrane glycolipids, which may protrude less from the cell surface. Thus, *H. pylori* adheren-
ence during chronic infection might involve two separate receptor-ligand interactions—one at “arm’s length” mediated by Leb, and another, more intimate, weaker, and slEx-mediated adherence. The weakness of the slEx-mediated adherence, and its metastable ON/OFF switching, may benefit \textit{H. pylori} by allowing escape from sites where bactericidal host defense responses are most vigorous (Fig. 6C). In summary, we found that \textit{H. pylori} infection elicits gastric mucosal sialylation as part of the chronic inflammatory response and that many virulent strains can exploit Selectin mimicry and thus “home in” on inflammation-activated domians of sialylated epithelium, complementing the baseline level of Leb receptors. The spectrum of \textit{H. pylori} adhesion-receptor interactions is complex and can be viewed as adaptive, contributing to the extraordinary chronicity of \textit{H. pylori} infection in billions of people worldwide, despite human genetic diversity and host defenses.

References and Notes
14. Strains and culture, adherence in situ (AIS), \textit{H. pylori} overlying to TLC, isolation and identification of the s-di-Lex GSL, apical localization of sLex antigen expression (fig. S2), retagging and identification of SabA/sabA, alignment of JHP662/JHP659 (fig. S1), construction of adhesin gene mutants, analyses of sabA by PCR, RIA and Scatchard analyses, gastric biopsies from patients and monkeys analyzed for \textit{H. pylori} binding activity and inflammation, and a summary of \textit{H. pylori} binding to glycosphingolipids (table S1) are available as supporting online material.
23. A. Arnqvist et al., in preparation.