Shielding of a Lipooligosaccharide IgM Epitope Allows Evasion of Neutrophil-Mediated Killing of an Invasive Strain of Nontypeable Haemophilus influenzae

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ABSTRACT Nontypeable Haemophilus influenzae is a frequent cause of noninvasive mucosal inflammatory diseases but may also cause invasive diseases, such as sepsis and meningitis, especially in children and the elderly. Infection by nontypeable Haemophilus influenzae is characterized by recruitment of neutrophilic granulocytes. Despite the presence of a large number of neutrophils, infections with nontypeable Haemophilus influenzae are often not cleared effectively by the antimicrobial activity of these immune cells. Herein, we examined how nontypeable Haemophilus influenzae evades neutrophil-mediated killing. Transposon sequencing (Tn-seq) was used on an isolate resistant to neutrophil-mediated killing to identify genes required for its survival in the presence of human neutrophils and serum, which provided a source of complement and antibodies. Results show that nontypeable Haemophilus influenzae prevents complement-dependent neutrophil-mediated killing by expression of surface galactose-containing oligosaccharide structures. These outer-core structures block recognition of an inner-core lipooligosaccharide epitope containing glucose attached to heptose HepIII-β1,2-Glc by replacement with galactose attached to HepIII or through shielding HepIII-β1,2-Glc by phase-variable attachment of oligosaccharide chain extensions. When the HepIII-β1,2-Glc-containing epitope is expressed and exposed, nontypeable Haemophilus influenzae is opsonized by naturally acquired IgM generally present in human serum and subsequently phagocytosed and killed by human neutrophils. Clinical nontypeable Haemophilus influenzae isolates containing galactose attached to HepIII that are not recognized by this IgM are more often found to cause invasive infections.

IMPORTANCE Neutrophils are white blood cells that specialize in killing pathogens and are recruited to sites of inflammation. However, despite the presence of large numbers of neutrophils in the middle ear cavity and lungs of patients with otitis media or chronic obstructive pulmonary disease, respectively, the bacterium nontypeable Haemophilus influenzae is often not effectively cleared from these locations by these immune cells. In order to understand how nontypeable Haemophilus influenzae is able to cause inflammatory diseases in the presence of neutrophils, we determined the mechanism that underlies resistance to neutrophil-mediated killing. We have shown that nontypeable Haemophilus influenzae prevents binding of antibodies of the IgM subtype through changes in their surface lipooligosaccharide structure, thereby preventing complement activation and clearance by human neutrophils.

Invasive disease caused by Haemophilus influenzae has decreased dramatically with the introductions of the H. influenzae type B conjugate vaccine (1). Currently, nontypeable H. influenzae (NTHi) is the most commonly isolated form of H. influenzae causing invasive infections in Europe (2). This group of H. influenzae strains lacks a capsule, which renders them more sensitive to antibacterial actions of the innate immune system. As such, NTHi is often found as a cause of mucosal inflammatory diseases, including otitis media (OM) (3), sinusitis (4), and exacerbations in patients with chronic obstructive pulmonary disease (COPD) (5). However, NTHi can also cause more invasive diseases, such as sepsis and meningitis (6). In all these situations, NTHi encounters the antimicrobial activity of the host’s immune system and therefore has developed mechanisms to survive and multiply during infection.

The immune response to NTHi includes secretion of cytokines and chemokines by the respiratory epithelium and resident immune cells, which attracts various types of nonresident immune cells, including large numbers of neutrophils, to the site of inflammation (7). Neutrophils possess multiple antimicrobial activities contributing to the clearance of bacterial pathogens, including the generation of reactive oxygen species (ROS), release of antimicrobial peptides and proteases from their granules, formation of extracellular traps (neutrophil extracellular traps [NETs]), and potent phagocytic capacity (8). Even though neutrophils are specialized killers, these cells are often not able to clear NTHi
Table 1: R2866 mutant library challenged with or without neutrophils with active complement for 2 h

<table>
<thead>
<tr>
<th>Total no. of</th>
<th>Total no. of</th>
<th>Fold</th>
<th>Adjusted</th>
<th>Gene locus</th>
<th>Gene name</th>
<th>Product</th>
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<tr>
<td>pseudoreads,</td>
<td>pseudoreads,</td>
<td>change</td>
<td>P</td>
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<tr>
<td>NHS</td>
<td>NHS + neutrophils</td>
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<td>value</td>
<td></td>
<td></td>
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<tr>
<td>379</td>
<td>5</td>
<td>–71.7</td>
<td>3.3E – 17</td>
<td>R2866_0222</td>
<td>galE</td>
<td>UDP-glucose 4-epimerase</td>
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<tr>
<td>260</td>
<td>6</td>
<td>–41.0</td>
<td>1.1E – 09</td>
<td>R2866_1061</td>
<td>rfaE</td>
<td>Fused heptose 7-phosphate kinase/heptose 1-phosphate adenylyltransferase</td>
</tr>
<tr>
<td>113</td>
<td>4</td>
<td>–26.4</td>
<td>2.2E – 06</td>
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<td>rfaD</td>
<td>ADP-1-glycero-3-manno-heptose-6-epimerase</td>
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<td>5</td>
<td>–23.6</td>
<td>1.0E – 06</td>
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<td>rfaI</td>
<td>ADP-heptose-LOS heptosyltransferase II</td>
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<td>293</td>
<td>13</td>
<td>–21.7</td>
<td>3.6E – 14</td>
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<td>lic2A</td>
<td>Lipoisogalactosylceramide biosynthesis protein Lic2A</td>
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<td>359</td>
<td>37</td>
<td>–9.5</td>
<td>2.9E – 08</td>
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<td>galU</td>
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<td>R2866_0326</td>
<td>lgtC</td>
<td>1,4-alpha-galactosyltransferase (LgtC)</td>
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</table>

*Genes related to LOS biosynthesis with a >5-fold decrease in total pseudoreads for NHS plus neutrophils compared to pseudoreads for NHS, P < 0.05, were selected.

Infections. Neutrophil recruitment has even been shown to be an advantage for NTHi survival by eliminating sensitive competitors like Streptococcus pneumoniae (9). In addition, NTHi actively induces NET formation in vitro, which may promote its survival (10, 11).

Bacteria need to be opsonized by antibodies and/or complement factors, such as C3b and C5b, to be efficiently phagocytosed by neutrophils (12). Unencapsulated bacteria, like NTHi, are particularly susceptible to complement-mediated killing and subsequent phagocytosis by neutrophils due to the lack of a protective surface structure. In response to this threat, NTHi has developed multiple strategies to evade the bactericidal activity of the human complement system. For instance, NTHi binds the complement control proteins C4b binding protein (C4BP) and factor H (13, 14). In addition, variation and modifications in its lipooligosaccharide (LOS) composition have been shown to prevent complement activation (15–18). The LOS structure of NTHi consists of three parts: (i) lipid A, (ii) an inner core comprised of a single 3-deoxy-o-manno-octulosonic acid (Kdo) linked to three conserved heptoses (Hep), and (iii) an outer core containing variable oligosaccharide extensions (19). Specific LOS structures have been shown to prevent binding of antibody and complement factor C4b, which increases their resistance to complement-mediated lysis (15, 16). In addition, NTHi prevents recognition by antibodies through incorporation of phosphorylcholine (PCho) and other “self-antigens” into the LOS structure (17, 18). However, mechanisms that prevent neutrophil-mediated killing are incompletely understood.

We used transposon sequencing (Tn-seq) technology to identify genes required for NTHi to survive in the presence of human neutrophils. We identified an important role for phase-variable incorporation of oligosaccharides into the LOS outer core, shielding an epitope that is recognized by naturally acquired IgM, thereby preventing complement activation, opsonization, and killing by human neutrophils.

Results

Identification of genes important for survival in the presence of human neutrophils. To identify genes that were important for resistance to neutrophil-mediated killing, we used Tn-seq to compare survival of transposon mutants of the invasive clinical isolate R2866. Mutants were screened in the presence of 10% pooled normal human serum (NHS) containing opsonizing antibodies and active complement only as a control and NHS in the presence of freshly isolated human neutrophils from peripheral blood as a challenge condition (see Fig. S1A in the supplemental material). Viable counts of the mutant library exposed to NHS or NHS with neutrophils did not differ at the start of the experiment, after 2 h of incubation, or after the 3 h of growth in sBHI (brain heart infusion [BHI] broth [Becton, Dickinson] supplemented with 2% Fildes enrichment [Thermo Scientific] and 2 µg/ml β-NAD [Sigma-Aldrich]) needed to obtain sufficient DNA for genomic DNA isolation (see Fig. S1B).

Tn-seq analysis identified a total of 20,759 TA insertion sites with at least 10 reads for the control condition. These insertion sites included 17,507 insertions into 1,498 out of the 1,876 predicted genes in the R2866 genome. Among others, we found that transposon insertions in multiple genes known to be involved in lipooligosaccharide (LOS) biosynthesis conferred a significant decrease in survival in the presence of neutrophils (Table 1), with the largest effects seen for a strain carrying transposon mutations in the galE gene, encoding a UDP-galactose 4-epimerase needed for reversible conversion of UDP-glucose to UDP-galactose (20).

Neutrophil-mediated killing of R2866Δlic1/galE is dependent on phagocytosis and serine-protease activity. To study the effects of the galE gene on resistance to neutrophil-mediated killing, we replaced the entire galE gene with a spectinomycin resistance cassette. In preliminary experiments, we observed increased neutrophil-mediated killing of the R2866ΔgalE mutant (data not shown) but also selection for phase variants incorporating PCho into the LOS of the R2866ΔgalE mutant, as determined by TEPC-15 binding assessed by flow cytometry (see Fig. S2A in the supplemental material). PCho is known to bind C-reactive protein and germline-encoded IgM (21, 22) and modulates resistance to complement through decreased binding of IgG (17). Therefore, we inactivated PCho incorporation by deletion of either lic1A or lic1D (further referred to as lic1 mutants) to evaluate the effect of galE or other gene deletions on resistance to neutrophil-mediated killing in the absence of this structure. Growth of R2866Δlic1 and R2866Δlic1/galE in sBHI were not significantly different (see Fig. S2B).

Neutrophil-mediated killing of R2866Δlic1/galE in 5% NHS was dose dependent, with an NTHi/neutrophil ratio of 1:100, resulting in ~80% killing (Fig. 1A), which was used in all the following experiments. Neutrophil-mediated killing was completely dependent on the presence of active complement, since neutrophils
with heat-inactivated NHS were not able to kill R2866Δlic1 or R2866Δlic1/galE (Fig. 1B).

Next, we determined by which mechanisms R2866Δlic1/galE was killed by human neutrophils. Cytochalasin D and protease inhibitor (PI) cocktail showed complete inhibition of neutrophil-mediated killing of R2866Δlic1/galE (Fig. 1C). Of note, we were not able to determine the contribution of reactive oxygen species (ROS) in neutrophil-mediated killing, since diphenylene iodonium (DPI) affected survival of NTHi at concentrations needed to inhibit ROS production by neutrophils (data not shown). We used specific inhibitors to elucidate which type of protease was responsible for neutrophil-mediated killing of NTHi. Whereas myeloperoxidase (MPO) inhibitor and the cysteine protease inhibitor E-64 showed no effect on bactericidal activity of neutrophils, the serine protease inhibitors 4-(2-aminoethyl) benzenesulfonyl fluoride hydrochloride (AEBSF) and diisopropyl fluorophosphate (DFP) showed complete inhibition of neutrophil-mediated killing of R2866Δlic1/galE (Fig. 1D).

Therefore, we conclude that neutrophil-mediated killing of R2866Δlic1/galE is dependent on phagocytosis that involves complement-dependent uptake of the bacteria and activity of serine proteases.

FIG 2 Increased IgM and C3 binding to the bacterial surfaces of R2866Δlic1/galE. R2866Δlic1 and R2866Δlic1/galE were incubated for 15 min with 5% NHS at 37°C, and binding of human IgG (A), IgM (B), or complement factor C3 (C) to the bacterial surface was determined by flow cytometry. (D) R2866Δlic1/galE was incubated for 15 min with 5% NHS or 5% IgM-depleted serum at 37°C, and binding of human IgM to the bacterial surface was determined by flow cytometry. R2866Δlic1 and R2866Δlic1/galE were incubated for 15 min with 5% NHS from individual donors (E), human nasal airway surface fluid (F), or 10% cord blood plasma at 37°C (G), and binding of IgM to the bacterial surface was determined by flow cytometry. Statistical significance was determined using an unpaired Student t test. NS, not significant; *, P < 0.05; **, P < 0.01; ***, P < 0.001.

The R2866Δlic1/galE mutant shows increased IgM and C3 binding. Since neutrophil-mediated killing of the R2866Δlic1/galE mutant was dependent on phagocytosis, we compared IgG, IgM, and C3 deposition on the bacterial surface of R2866Δlic1 and R2866Δlic1/galE by flow cytometry. Whereas binding of IgG was not different (Fig. 2A), a marked increase in IgM binding (Fig. 2B) and C3 deposition (Fig. 2C) was found on the surface of the R2866Δlic1/galE mutant compared to findings for the R2866Δlic1 control. Binding of IgM was needed for neutrophil-mediated killing of the R2866Δlic1/galE mutant, since depletion of IgM (see Fig. 2C in the supplemental material) abrogated neutrophil-mediated killing completely (Fig. 2D). Significant increased IgM binding was observed not only with pooled NHS but also when donor specific NHS (Fig. 2E) or human nasal airway surface fluid (Fig. 2F) was used.

Serum IgM can be divided into germ line-encoded IgM and naturally acquired IgM synthesized after immune stimulation (21). IgM is not able to pass the placental barrier; therefore, IgM present in cord blood plasma is exclusively germ line encoded. No difference in IgM binding (Fig. 2G) or IgG binding (see Fig. S2D in the supplemental material) between R2866Δlic1 and R2866Δlic1/galE was observed with cord blood plasma. Altogether, we conclude that IgM that recognizes an epitope(s) on the R2866Δlic1/galE mutant was acquired from previous exposure and is generally present in human serum.

IgM binds to HepIII-β1,2-Glc in the R2866Δlic1/galE LOS structure. Next, we set out to identify the specific LOS epitope(s)
The presence of glucose (Glc) attached to HepIII in a β1,2 linkage was needed for recognition by IgM, because the R2866Δlic1/lgtF/lpsA mutant lacking any oligosaccharide chains on HepI and HepIII showed a significant decrease in IgM binding compared to the R2866Δlic1/lgtF/lc2A mutant (Fig. 3B). In accordance with the findings for R2866Δlic1/galE, an increase in IgM binding to the R2866Δlic1/lgtF/lc2A mutant but not the other LOS mutants increased neutrophil-mediated killing significantly (Fig. 3C).

Increased binding of IgM to the bacterial surface of the R2866Δlic1/lgtF/lc2A mutant was due to an altered LOS structure, because marked binding of IgM to the LOS of the R2866Δlic1/lgtF/lc2A mutant was detected, whereas binding of IgM was nearly undetectable for the R2866Δlic1 mutant and increased slightly for the R2866Δlic1/lc2A mutant (Fig. 3D). From these data, we conclude that IgM binds an epitope that contains HepIII-β1,2-Glc on the R2866Δlic1/lgtF/lc2A mutant.

To determine whether IgM recognized a similar epitope in the LOS of the R2866Δlic1/galE and R2866Δlic1/lgtF/lc2A mutants, we preincubated NHS with LOS from the R2866Δlic1/galE, R2866Δlic1/lgtF/lc2A, or R2866ΔlpsA/lgtF as a control, to compete with IgM binding to the bacterial surface of the R2866Δlic1/lgtF/lc2A mutant. Preincubation of NHS with LOS from the R2866ΔlpsA/lgtF did not decrease IgM binding to the R2866Δlic1/lgtF/lc2A mutant. However, addition of LOS from either R2866Δlic1/lgtF/lc2A or R2866Δlic1/galE decreased IgM binding to the R2866Δlic1/lgtF/lc2A mutant in a dose-dependent manner (Fig. 3E), which confirmed that IgM from human serum bound a similar epitope on the LOS of the R2866Δlic1/galE and R2866Δlic1/lgtF/lc2A mutants. From these data, we conclude that human serum contains naturally acquired IgM recognizing an epitope that includes HepIII-β1,2-Glc and that an oligosaccharide chain extension on HepIII-β1,2-Glc, as well as on oligosaccharides on HepI and HepIV, block binding of IgM to the R2866Δlic1 control strain.

Phase-variable incorporation of galactose on HepIII-β1,2-Glc prevents neutrophil-mediated killing. The linkage to HepIII can be substituted with galactose (Gal) by the phase-variable gene lic2A (24, 25) (Fig. 4A). While we conducted experiments with strain Rd, we observed increased IgM binding (Fig. 4B) and neutrophil-mediated killing (Fig. 4C) for both RdΔlic1/lgtF and RdΔlic1/lgtF/lc2A, whereas binding of IgG was similar (see Fig. S2F in the supplemental material). The lack of difference for IgM binding and neutrophil-mediated killing between RdΔlic1/lgtF and RdΔlic1/lgtF/lc2A would suggest that lic2A was “phase off” in strain RdΔlic1/lgtF, which we confirmed by sequencing (see Fig. S3). Accordingly, we observed that sequential exposure (3 rounds) of RdΔlic1/lgtF to NHS and neutrophils selected for RdΔlic1/lgtF with lic2A “phase on” (a shift from 23 to 22 tandem repeats of CAAT within the lic2A gene) (see Fig. S3). Phase variation of lic2A coincided with an increased LOS size (Fig. 4D), decreased IgM binding (Fig. 4E), and increased resistance to neutrophil-mediated killing (Fig. 4F), whereas no difference in IgG binding was observed (see Fig. S2G). We confirmed that lic2A phase-on selection was essential for decreased IgM binding and neutrophil-mediated killing because RdΔlic1/lgtF/lc2A remained sensitive to neutrophil-mediated killing after serial treatment with NHS and neutrophils (3 rounds) (Fig. 4G). Therefore, these data show that phase-variable incorporation of lic2A mutant increased IgM binding significantly (Fig. 3B).
galactose onto HepIII-β1,2-Glc by Lic2A prevents binding of IgM and increases resistance to neutrophil-mediated killing.

Binding of IgM to HepIII-β1,2-Glc but not HepIII-β1,2-Gal contributes to neutrophil-mediated killing of NTHi. Incorporation of glucose onto HepIII is dependent on the lpsA gene. Besides incorporation of glucose onto HepIII, LpsA can also incorporate galactose, which is strain specific and determined by a single amino acid difference at position 151 (26) (see Fig. S4A in the supplemental material). In order to determine the specificity for IgM binding, we constructed an Rdlic1/lgtF/lic2A strain that has a HepIII-β1,2-Glc epitope (25) (Fig. 5A) and an Rdlic1/lgtF/lic2A strain with the lpsA gene from strain R2846 that has a HepIII-β1,2-Gal epitope (Fig. 5B), and lpsA gene replacement was confirmed by sequencing (see Fig. S4B). A change from glucose to galactose attached to HepIII decreased IgM binding (Fig. 5C) but not IgG binding (see Fig. S2H), as measured by flow cytometry and Western blot analysis (Fig. 5D). More importantly, neutrophil-mediated killing of the Rdlic1/lgtF/lic2A mutant was significantly decreased with incorporation of galactose on HepIII for the Rdlic1/lgtF/lic2A R2846 lpsA mutant (Fig. 5E).

Invasive NTHi isolates incorporate galactose onto HepIII more frequently. The presence of Thr at position 151 in the LpsA protein results in specificity for galactose, whereas the presence of Cys, Ala, or Met results in the incorporation of glucose. From 82 recently published NTHi genomes (27), 13 publically available NTHi genomes, and 10 additional clinical NTHi strains, 103 (98%) contained a single amino acid difference at position 151 in the LpsA gene, indicating that ~2% of NTHi strains do not incorporate any oligosaccharides on HepIII. ClustalW2 alignment (http://www.ebi.ac.uk/Tools/msa/clustalw2/) of the LpsA proteins showed the presence of Thr in 26/105 (25%), Cys in 61/105 (58%), Met in 15/105 (14%), or Ala in 1/105 (1%) (see Fig. S4A in the supplemental material) on position 151, predicting incorporation of glucose or galactose in 73% or 25% of the strains, respectively.

Of the NTHi isolates, 22 were carriage strains, 41 were obtained from patients with otitis media (OM), 25 were from patients with COPD, and 17 were invasive isolates. The percentage of strains predicted to incorporated galactose or no saccharide (no lpsA gene) onto HepIII was 14% for carriage strains, whereas this was 29% and 24% for strains isolated from patients with OM or COPD, respectively (Table 2). Incorporation of galactose or no saccharide onto HepIII was predicted for 41% of the strains col-
lected from patients with invasive disease (Table 2), which was ~3-fold more frequent than for carriage strains, indicating a relationship between incorporation of galactose or no saccharide onto HepIII and the ability to cause invasive disease (Pearson chi-square, 3.815; \( P = 0.05 \)). Collectively, these data support a role for incorporation of galactose or no saccharide onto HepIII, thereby preventing binding of IgM, which increases resistance to neutrophil-mediated killing, although the presence and activity of other glycosyltransferases such as lic2A, as shown in Fig. 4, also contribute to the overall resistance phenotype.

**DISCUSSION**

In this study, we used Tn-seq to identify genes important for survival in the presence of pooled NHS with or without freshly isolated human neutrophils. Multiple genes involved in LOS biosynthesis were identified (Table 1), including the rfaD, rfaE, rfaF, and waaQ genes, important for synthesis of the LOS inner core (28, 29). The rfaD gene mutant showed decreased virulence in a chimera model for OM (30) and increased killing by neutrophil extracellular traps (NETs) (11), emphasizing a critical role for the LOS inner core in virulence of NTHi; however, the mechanisms remained unexplored.

Multiple genes involved in synthesis of the variable LOS outer core, including galE, galU, lic2A, and lgtC, were shown in our work to be important in resisting killing by human neutrophils. Many of these genes have previously been shown to contribute to resistance to complement-mediated killing in the absence of neutrophils. Erwin et al., for example, described an important role for lgtC in resistance to complement-mediated killing of strain R2866 (31), and each of these genes has been identified in recently published transposon mutagenesis screens for genes involved in resistance to the complement-dependent bactericidal effect of serum (15, 32). The activation of complement on the bacterial surface has both direct antimicrobial activity (formation of the membrane attack complex) and indirect effects (opsonization). Throughout our study, we have compared NHS containing active complement with and without neutrophils, controlling for the effect of complement alone and allowing us to focus on the additional contribution of neutrophils to NTHi killing.

Truncations of the R2866 LOS outer core resulted in increased binding of IgM from pooled NHS. Even though detectable levels of IgG binding were observed for NTHi with or without an intact LOS outer core, increased binding of IgM was required to initiate sufficient complement activation to promote neutrophil-mediated uptake and killing. In contrast, the amount of complement deposition resulting from IgG binding did not appear to be as effective at opsonizing the bacteria.

The contribution of IgM binding to the bacterial surface of NTHi to efficient complement-mediated killing has been demonstrated in various studies. We have previously shown that the level of IgM binding correlated with complement-mediated killing for NTHi strains collected from children with OM (15) and complement-resistant NTHi isolates from patients with COPD showed decreased IgM binding (32). Decreased binding of IgM to complement-resistant isolates is likely to be multifactorial, because changes in the LOS, as well as exclusion of phospholipids from the outer leaflet of the bacterial membrane, decreased IgM binding and increased resistance to complement-mediated killing (15, 32). Therefore, it appears that IgM recognition of NTHi plays an important role in controlling infections with NTHi. This is corroborated by clinical data from patients with hyper-IgM syndrome, who have a significantly lower risk of NTHi carriage than children with panhypogammaglobulinemia, suggesting that IgM antibodies, even in the absence of IgG or IgA, are protective and contribute to the prevention of respiratory tract colonization and infection (33).

Most vaccine studies for NTHi are focused on the use of immunogenic membrane-exposed proteins (34). However, antigenic variation and the absence of certain proteins in selected NTHi isolates make it difficult to formulate a broadly protective protein-based vaccine. Therefore, LOS might be an interesting alternative, and this concept is supported by a vaccination study with protein-conjugated LOS (35). Although the LOS of NTHi is heterogeneous as well, immunization against specific LOS epitopes masking immune-dominant structures might be an interesting alternative, and several studies demonstrate the potential of opsonizing LOS antibodies in opsonophagocytosis and protection in mouse models. Mouse monoclonal antibodies recognizing NTHi LOS after intraperitoneal immunization were shown to be mainly IgM, and selected clones conferred bactericidal activity and increased phagocytosis by human neutrophils (36). A mouse immunization study with *M. catarrhalis* was shown to induce cross-reactive IgM recognizing *H. influenzae* LOS, which increased bactericidal activity in the presence of complement, demonstrating that antibodies to single LOS epitopes could be protective (37).

We identified an important role for binding of IgM to LOS in neutrophil-mediated killing. In order to determine the exact epitope recognized by IgM, we generated a series of mutant strains that either had truncated oligosaccharide extensions or a complete absence of oligosaccharides on HepI or HepII. Although we have not confirmed the LOS structures by mass spectrometry, altered size as confirmed by Tris-Tricine gel electrophoresis and consistent results for strains Rd, R2846 (data not shown), and R2866 present strong evidence that IgM from human serum recognizes an epitope that contains HepIII-β1,2-Glc but not HepIII-β1,2-Gal. Both galactose and glucose can be attached to HepIII in a β1,2 or β1,3 linkage (26), but we have not addressed whether the linkage has effect on binding of IgM.

Although NTHi can incorporate a galactose on HepIII, thereby increasing its resistance to neutrophil-mediated killing, in 73% of NTHi strains incorporation of a glucose at this site is predicted (Table 2). Therefore, it is tempting to speculate that the presence of glucose on the HepIII might have advantages for NTHi under specific conditions, like colonization of the upper respiratory tract. Such apparent discrepancy is also found for incorporation of PCho into the LOS structure. Although PCho is recognized by C-reactive protein (CRP) and germ line-encoded IgM (21, 22), thereby activating the classical complement pathway, the presence of PCho contributes in colonization in animal models (17) and in

**TABLE 2** Predicted distribution of glucose or galactose (Gal) incorporation with HepIII by LpsA in 105 clinical NTHi isolates

<table>
<thead>
<tr>
<th>Incorporation</th>
<th>Carriage</th>
<th>Otitis media</th>
<th>COPD</th>
<th>Invasive</th>
<th>Total</th>
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<td>Glc</td>
<td>19 (86.4)</td>
<td>29 (70.7)</td>
<td>19 (76.0)</td>
<td>10 (58.8)</td>
<td>77</td>
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<td>Gal or no saccharide</td>
<td>3 (13.6)</td>
<td>12 (29.3)</td>
<td>6 (24.0)</td>
<td>7 (41.2)</td>
<td>28</td>
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<table>
<thead>
<tr>
<th>No. (%) of isolates</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glc</td>
<td>77</td>
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<tr>
<td>Gal or no saccharide</td>
<td>28</td>
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</table>
a human colonization model (38). Similar factors might be selecting for incorporation of glucose onto HepIII, but to our knowledge this has not been investigated.

Whereas incorporation of a galactose on HepIII is considered to be a terminal moeity, glucose on HepIII can be substituted with galactose depending on lic2A gene activity (19), which is controlled by phase variation, a mechanism that switches translation of genes on or off (39). Phase-variable on-off translation of genes is a stochastic process dependent on slipped-strand mispairing of tandem repeats present in the gene, which occurs with a high frequency (10⁻² to 10⁻³ times per generation) and leads to switching the coding region in or out of frame. We showed that selection for lic2A phase-on variants incorporating oligosaccharides onto HepIII-β1,2-Glc blocked binding of IgM, which prevented neutrophil-mediated killing. These experiments are in accordance with experiments performed by Clark et al., where serial exposure to NHS selected for lic2A phase-on variants and increased complement resistance through decreased binding of IgG (40). Since this is a phase-variable process, it raises the question of the advantage for NTHi in switching between these two LOS types. As for PCho, oligosaccharide extensions on HepIII-β1,2-Glc might be an advantage or disadvantage for NTHi depending on the location where it resides in the human host. Shielding of conserved immune-dominant epitopes with more-variable structures has been observed not only for NTHi but also for other pathogens, such as S. pneumoniae. For instance, pneumococcal surface protein A (PspA) binds to PCho and thereby blocks binding of CRP to the bacterial surface, preventing C3 deposition (41).

Because IgM recognizing an epitope containing HepIII-β1,2-Glc was not present in cord blood plasma, we concluded that it is not germ line encoded but is acquired in human serum from previous exposure. In contrast, we were unable to identify significant levels of IgG recognizing this epitope. There is evidence that a large proportion of memory B cells do not class switch but give rise to a population called IgM⁺CD27⁺ memory B cells producing antigen-specific IgM. This population of memory B cells accumulates somatic mutations, although to a lower extent than IgG-producing B cells, but does not class switch (42, 43), and we propose that IgM recognizing an epitope that includes HepIII-β1,2-Glc is produced by this type of memory B cell. Although the origin and function of IgM⁺CD27⁺ memory B cells are under debate (44), they appear to be an important part of the adaptive immune response to various pathogens. The percentages of IgM⁺CD27⁺ memory B cells in the peripheral blood of children are low, increase to almost 20% in adults, and decline in the elderly (45), which corresponds with susceptibility to bacterial infections in children and the elderly. An important protective role for IgM⁺CD27⁺ memory B cells was shown in patients with common variable immunodeficiency (CVID) or splenectomized or asplenic patients, where the presence of antcapsular IgM⁺CD27⁺ memory B cells protected against bacterial pneumonia (46, 47). In addition, transient predisposition to infections caused by S. pneumoniae in very young children (<2 years) was associated with the lack of IgM⁺CD27⁺ memory B cells and antipneumococcal capsular IgM (47). Altogether, IgM appears to play an important role in the adaptive immune response to pathogens, and exposing the immune system through vaccination might increase the ability of neutrophils to clear NTHi infections.

In conclusion, we have shown that IgM binding to the NTHi LOS facilitates efficient neutrophil-mediated killing of NTHi, but this pathogen has developed at least three mechanisms that prevent binding of IgM to HepIII-β1,2-Glc: (i) oligosaccharide extensions of HepI and possibly other heptose residues, (ii) phase-variable incorporation of galactose onto HepIII-β1,2-Glc, and (iii) incorporation of galactose onto HepIII. Our findings suggest that strategies to increase binding of IgM might enhance opsonization and phagocytic activity of human neutrophils and thereby limit infections by NTHi.

MATERIALS AND METHODS

Bacterial strains and growth conditions. Strains used in this study are listed in Table S1 in the supplemental material (53–58). Bacteria were grown with shaking at 37°C in brain heart infusion (BHI) broth (Becton, Dickinson) supplemented with 2% Fildes enrichment (Thermo Scientific) and 2 μg/ml β-NAD (Sigma-Aldrich) (sBHI). Viable bacterial counts were determined by plating serial dilutions in phosphate-buffered saline (PBS) on sBHI agar plates grown at 37°C with 5% CO₂. Optical density was measured at 620 nm. For mutant library and gene mutants, 100 μg/ml spectinomycin (Calbiochem), 20 μg/ml kanamycin (Fisher Bioreagents), or 12.5 μg/ml tetracycline (Sigma-Aldrich) was used.

Human neutrophils, normal human serum, and human nasal airway surface fluid. Blood was drawn from healthy adult donors in sodium-heparin anticoagulation tubes (BD Vacutainer) and isolated using Ficoll-Paque (GE Healthcare) as described previously (48). Before use, neutrophils were taken up in Hanks’ buffered salt solution (HBSS) without phenol red containing Ca²⁺ and Mg²⁺ plus 0.1% gelatin to the desired concentration. All experiments were performed with the same batch of pooled normal human serum (NHS) containing opsonizing antibodies and active complement obtained from GTI Diagnostics (catalogue no. PBS-N100). For IgM depletion, 2 ml of 20% NHS in PBS was incubated with 200 μl of PBS-washed Sepharose beads coupled to anti-human IgM antibody (Sigma). After 2 h of incubation while shaking at 4°C, Sepharose beads were removed by centrifugation, and sera were diluted to 10% with PBS and immediately stored at −80°C. Donor-specific NHS was obtained from healthy adult volunteers, using serum tubes (BD Vacutainer), centrifuged, and stored immediately at −80°C. Human nasal airway surface fluid was obtained from a healthy adult volunteer as described previously (49).

Identifying NTHi genes essential for survival with NHS and human neutrophils. Genomic DNA from NTHi strain R2866 was isolated from mid-log-phase cultures using the Qiagen Genomic-tip 20/G tips (Qiagen), following the manufacturer’s protocol. The NTHi R2866 mariner7-Mmel transposon mutant library was generated as described previously for NTHi 86-028NP (50).

The NTHi R2866 mariner7-Mmel transposon mutant library was diluted to 2 × 10⁷ CFU/ml in HEPES-buffered RPMI containing 1 μg/ml hemin and 2 μg/ml β-NAD and incubated for 2 h in the presence of 10% normal human serum (control) or 10% normal human serum with 2 × 10⁷ neutrophils/ml (multiplicity of infection [MOI], 0.1) in quadruplicate at 37°C (end volume, 1 ml). After challenge, neutrophils were lysed by adding 100 μl 10% saponin in PBS and incubated for 10 min at room temperature. Subsequently, 4 ml sBHI was added, and the mutant library was grown to an optical density at 620 nm (OD₆₂₀) of ~0.2 (~4 h), and chromosomal DNA was isolated for Tn-seq analysis. Generation times were confirmed by viable bacterial counts (see Fig. SB in the supplemental material). Genomic DNA was isolated using a DNeasy Blood & Tissue kit (Qiagen), following the manufacturer’s protocol. A readout of the mutant library and data analysis were performed as described previously (50). Analysis data can be found at http://bamics2.cmbi.ru.nl/websoftware/essentials/essentials_run.php?session=essentials%neutrophil.

Generation of NTHi-directed gene replacement mutants. Bacterial genomic DNA was isolated using a DNeasy Blood & Tissue kit (Qiagen), following the manufacturer’s protocol. Directed NTHi gene replacement mutants were generated by allelic exchange of donor genomic DNA or by allelic exchange of the target gene with an antibiotic resistance marker, as

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described previously (50). Mutants were selected by plating on sBHI plates containing 100 μg/ml spectinomycin, 20 μg/ml kanamycin, or 12.5 μg/ml tetracycline and validated by PCR. All primers used in this study are listed in Table S1 in the supplemental material.

**lpsA** gene replacement in RdΔlic1/lgtF/lsc2A. The R2846 lpsA gene was PCR amplified using the primers NTHi_lpsA_F_uptake and NTHi_lpsA_R_uptake (see Table S1 in the supplemental material), containing uptake sequences for increased transformation efficiency. The PCR product was purified using the QIAquick PCR purification kit (Qiagen), following the manufacturer’s protocol, and 5 μg PCR product or water as a control was incubated 1 h with 500 μl of 1-M IV competent (51) RdΔlic1/lgtF/lsc2A bacteria. Five hundred microliters sBHI was added to enable growth for 2 h at 37°C with shaking at 225 rpm. Cultures were washed without phenol red containing Ca²⁺ and Mg²⁺ plus 0.1% gelatin and diluted to −1 × 10⁶ bacteria/ml. One hundred microliters culture (−1 × 10⁹ bacteria) was incubated with 5% NHS for 30 min, plated on sBHI, and grown overnight at 37°C plus 5% CO₂ to select for complement-resistant transformants. Complement resistance assay was repeated with the surviving bacteria to enrich the selection. Single colonies were picked for growth and DNA isolation, and the lpsA gene was PCR amplified with the primers NTHi_lpsA_F2 and NTHi_lpsA_R1 (see Table S1). Replacement of the Rd lpsA gene (cytostate [C] at amino acid position 151) with the R2846 lpsA gene (threonine [T] at amino acid position 151) was confirmed by sequencing (see Fig. S4).

**Flow cytometric analysis.** Bacteria were grown to an OD₆₀₀ of ~0.6 in sBHI medium, washed with HBSS without phenol red containing Ca²⁺ and Mg²⁺, and diluted to an OD₆₀₀ of 0.2. Surface opsonization with serum was performed by incubating 50 μl bacteria with 50 μl 10% pooled NHS, 10% cord blood plasma, or 1:250-diluted TEPC-15 in HBSS without phenol red containing Ca²⁺ and Mg²⁺ or human nasal airway surface fluid for 15 min at 37°C with 5% CO₂. Oposonized bacteria were fixed for 20 min with 2% paraformaldehyde, washed, and incubated with 1:500-diluted fluorescein isothiocyanate (FITC)-labeled polyclonal goat anti-human IgG, 1:50-diluted FITC-labeled μ-chain-specific goat anti-human IgM (Sigma-Aldrich), or 1:100-diluted FITC-labeled μ-chain-specific goat anti-mouse IgG, 1:50-diluted FITC-labeled λ-chain-specific goat anti-mouse IgG, plus 5% FCS for 30 min at 4°C. Bacteria were washed and resuspended in PBS for flow cytometry. Binding was detected by flow cytometry using a FACS LSR II instrument (BD Biosciences). Data were analyzed using the software program FlowJo version 7.6.3. Measurement of geometric mean fluorescence intensity (MFI) was depicted in arbitrary units (AU).

**Neutrophil killing assay.** Bacteria were grown to an OD₆₀₀ of ~0.6 in sBHI, washed with HBSS without phenol red containing Ca²⁺ and Mg²⁺, and diluted to 2 × 10⁷ CFU/ml in HBSS without phenol red containing Ca²⁺ and Mg²⁺ plus 0.1% gelatin. Neutrophils were resuspended in HBSS without phenol red containing Ca²⁺ and Mg²⁺ plus 0.1% gelatin to 4 × 10⁹/ml (ratio, 1:20), 1 × 10⁷/ml (ratio, 1:50), or 2 × 10⁷/ml (ratio, 1:100). For inhibition experiments, neutrophils (2 × 10⁷/ml) were preincubated with 20 μM cytochalasin D (Sigma), 1 μM protease inhibitor cocktail (Calbiochem), 1 mM mecloxoperoxide (MPO) inhibitor, 10 μM E-64 (Sigma), 500 μM AEBSF (Calbiochem), or 200 μM DFP (Sigma) for 15 min at 37°C with 5% CO₂. Next, 10 μl heat-inactivated NHS (H1-NHS) or NHS of the desired concentration, 45 μl bacteria, and 45 μl neutrophils were mixed and incubated for 30 min at 37°C with 5% CO₂. CFU counts were determined by plating 10-fold dilutions on sBHI plates and incubated overnight at 37°C with 5% CO₂. The number of repeats was counted from each sequence and used to determine reading frame status as in frame (ON) or out of frame (OFF) (see Fig. S3).

**Statistical analysis.** Statistical analyses were performed using GraphPad Prism version 5 (GraphPad Software), where a P value of <0.05 was considered significant. The specific statistical tests that were used for the various experiments are specified in the figure legends. The program SPSS version 22 (IBM) was used to analyze the predicted galactose or glucose incorporation with HPepI with a chi-square test.

**SUPPLEMENTAL MATERIAL**
Supplemental material for this article may be found at http://mbio.asm.org/lookup/suppl/doi:10.1128/mBio.01478-14/-/DCSupplemental.

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**REFERENCES**


29. Klein U, Rajewsky K, Küppers R. 1998. Human immunoglobulin (IgM+IgD+) peripheral blood B cells expressing the CD27 cell surface antigen carry somatically mutated variable region genes: CD27 as a general