Nontypeable *Haemophilus influenzae* releases DNA and DNABII proteins via a T4SS-like complex and ComE of the type IV pilus machinery

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Biofilms formed by nontypeable *Haemophilus influenzae* (NTHI) are central to the chronicity, recurrence, and resistance to treatment of multiple human respiratory tract diseases including otitis media, chronic rhinosinusitis, and exacerbations of both cystic fibrosis and chronic obstructive pulmonary disease. Extracellular DNA (eDNA) and associated DNABII proteins are essential to the overall architecture and structural integrity of biofilms formed by NTHI and all other bacterial pathogens tested to date. Although cell lysis and outer-membrane vesicle extrusion are possible means by which these canonic intracellular components might be released into the extracellular environment for incorporation into the biofilm matrix, we hypothesized that NTHI additionally used a mechanism of active DNA release. Herein, we describe a mechanism whereby DNA and associated DNABII proteins transit from the bacterial cytoplasm to the periplasm via an inner-membrane pore complex (TraC and TraG) with homology to type IV secretion-like systems. These components exit the bacterial cell through the ComE pore through which the NTHI type IV pilus is expressed. The described mechanism is independent of explosive cell lysis or cell death, and the release of DNA is confined to a discrete subpolar location, which suggests a novel form of DNA release from viable NTHI. Identification of the mechanisms and determination of the kinetics by which critical biofilm matrix-stabilizing components are released will aid in the design of novel biofilm-targeted therapeutic and preventative strategies for diseases caused by NTHI and many other human pathogens known to integrate eDNA and DNABII proteins into their biofilm matrix.

**Significance**

Extracellular DNA and DNABII proteins are essential structural components of the extracellular polymeric substance, or matrix, of the nontypeable *Haemophilus influenzae* biofilm; however, the mechanisms by which these elements are released from the bacterial cell for incorporation into the biofilm matrix are not yet characterized. Here, we propose a mechanism for active DNA release during biofilm formation that involves an inner-membrane complex (TraCG) and the ComE pore through which the type IV pilus is typically expressed. Knowledge of how and when DNA and DNABII proteins are released into the extracellular milieu for integration into the biofilm matrix will further our understanding of biofilm formation and maturation and, in turn, guide development of directed therapies for diseases with a biofilm etiology.
Aggregatibacter actinomycetemcomitans, therapeutic treatment with antiserum against the DNAbII family of proteins induced significant resolution of experimental periimplantitis (29). This same antiserum also disrupted multispecies biofilms in sputum solids recovered from pediatric cystic fibrosis patients (25). However, to date, the exact mechanis(m(s) by which NTHI releases DNA and DNAbII proteins into the extracellular milieu has not yet been fully characterized.

NTHI is a predominant causative agent of multiple upper and lower respiratory tract diseases, which include otitis media, sinusitis, bronchitis, chronic cough, and exacerbations of both cystic fibrosis and chronic obstructive pulmonary disease (40, 41). Biofilm formation by NTHI contributes greatly to the chronicity of these diseases. Given the predomiance and essential structural role of both extracellular DNA and DNAbII proteins within an NTHI biofilm, we used this pathogen as a model organism with which to determine the mechanis(m(s) and kinetics by which these critical components are released by this bacterium. DNA and DNAbII proteins are typically found within the bacterial cytoplasm, and must pass across both the inner and outer membranes for release into the extracellular environment. Whereas no active DNA secretion systems are characterized for NTHI, Neisseria, a closely related species, actively secretes single-stranded DNA via a T4SS (34, 35, 42, 43). The T4SS of Neisseria is composed of an inner-membrane complex formed by TraC, TraD, and TraG; TraB, which spans both membranes; an outer-membrane complex, formed by TraK and TraV; and several cytoplasmic chaperone proteins (34, 35, 42, 43). Herein we investigated the possibility that NTHI used a similar mechanism for transit of DNA and associated DNAbII proteins from the cytoplasm into the periplasm and, further, that this microbe used the ComE pore, through which the type IV pilus (Tfp) is typically expressed, to export the DNA into the extracellular environment. This mechanism for release of DNA and DNAbII proteins from NTHI was independent of cell lysis and not preceded by changes in bacterial cell size or shape. We hypothesize that this unique mechanism of controlled DNA and DNAbII protein release from NTHI contributes significantly to the structural stability and robust architecture of biofilms formed by NTHI as well as other pathogens that use a similar strategy for integration of eDNA and DNAbII proteins into the biofilm matrix.

Results
NTHI Released DNA and DNAbII Proteins Soon After Attachment to the Substratum. Within 3 h of inoculation of NTHI onto a chambered coverglass, a lattice-like network of extracellular dsDNA was observed on the coverglass surface (Fig. 1A). In addition, DNAbII proteins were detected bound with regular periodicity along these strands of eDNA and also positioned at the vertices of crossed strands of eDNA (Fig. 1B, red fluorescence). Because the inoculum consisted of NTHI in the mid-log phase of growth, we reasoned it unlikely that cell death was the primary mediator for the presence of the structured lattice of eDNA. For clarity, additional experiments were conducted with a viability stain to confirm this assertion. We next determined whether altruistic cell death by explosive cell lysis facilitated the observed deposition of DNA, as is described for Pseudomonas (36). Although a small number (<1 for every 1,000 cells) of NTHI did indeed form giant rounded cells similar in morphology to those described for Pseudomonas; these rounded cells did not form until much later in time [e.g., more than 3 h after inoculation compared with ≤1 h after incubation as reported for Pseudomonas (36)]. Moreover and importantly, these giant rounded cells were observed for up to 6 h of culture and never lysed. Conversely, once formed, 86% of large rounded Pseudomonas cells survive for <60 s before lysing (36). The limited (if any) bacterial cell death and absence of explosive cell lysis under the culture conditions we tested suggested that the observed release of eDNA and associated DNAbII proteins from NTHI very early in biofilm formation likely occurred via an alternative nonlytic mechanism.

NTHI Released DNA and DNAbII Proteins via a Non-Lysis-Dependent Mechanism. To visualize the release of DNA from NTHI during biofilm formation in vitro, we stained the NTHI outer membrane with FM1-43 membrane stain (Fig. 2, green fluorescence) and cultured the bacteria in the presence of the nucleic acid stain ethidium homodimer-2 (Fig. 2, red fluorescence), a membrane-impermeant stain that is only fluorescent when bound to DNA. As such, red fluorescence would indicate the presence of eDNA in the extracellular milieu or a bacterium with a compromised outer membrane. Via time-lapse fluorescence microscopy, we detected the release of DNA into the extracellular milieu by a subpopulation of NTHI within 10 to 120 min of inoculation, as evidenced by a “flare” of red fluorescence beyond the bacterial cell membrane (Fig. 24 and Movie S1). This release from a single site is more clearly viewed in Movie S2, which was captured by superresolution time-lapse microscopy. However, NTHI that released DNA by this mechanism did not form giant rounded cells or exhibit explosive cell lysis before these events. This unique method of DNA release occurred on average from 17 of every 1,000 bacterial cells (Fig. 3, solid red bar) and within 2 h of inoculation.

To both confirm that the observed DNA staining represented release of DNA from NTHI and not uptake of DNA from the environment (as had been clearly indicated by time-lapse microscopy) as well as validate the labeling of internal versus external DNA, we also reversed the use of the fluorochromes and now labeled intracellular DNA with the membrane-permeable stain Syto 9 and the bacterial outer membrane with the membrane stain FM4-64. Under the same culture conditions, intracellular DNA now appeared as a green fluorescent signal encircled by a red fluorescent ring that represented the bacterial outer membrane (Fig. 2B). As before, DNA was released (now seen as a green flare) from a subpopulation of NTHI without formation of a giant rounded cell (Fig. 2B). Intriguingly, regardless of the fluorochrome used to detect intra- versus extracellular DNA, the release appeared to originate from a single location along the long axis of the cell and at a single subpolar location (Fig. 2).

To reveal the approximate location of the DNA release from the bacterial cell, we immunolabeled cultures of whole unfixed NTHI for the presence of both eDNA and DNAbII proteins. By scanning transmission electron microscopy (STEM), eDNA and DNAbII proteins were observed associated with the bacterial membrane at a single subpolar location similar to that observed via each fluorescence

![Fig. 1. Detection of eDNA and DNAbII proteins early in biofilm formation in vitro. (A) Three hours after inoculation, eDNA released from NTHI was arranged in a lattice-like structure (white). (B) Overlay image depicts DNAbII proteins (red) associated with eDNA (white). DNAbII proteins appeared as punctate red fluorescent signals situated at vertices of crossed strands of eDNA (yellow arrows) and also positioned at regular intervals along the eDNA strands. Whole bacterial cells also appear red, as the antiserum against NTHI IHF also labels the bacterial cell (blue arrow). (Scale bars, 10 μm.)](E6633)
time-lapse microscopy strategy used (Fig. 4A). These corroborating data confirmed that NTHI released DNA and DNABII proteins from a discrete location of the bacterial outer membrane. The subpolar region of this DNA release appeared highly similar to the location from which we have shown the NTHI Tfp is expressed and that coincides with the location of the ComE pore (Fig. 4B). Further evidence of the release of DNA and DNABII proteins from a single subpolar site on the bacterial cell and their assembly into a lattice-like structure is provided in Fig. 4C. The NTHI Tfp is an adhesive protein that is extruded through the outer-membrane pore formed by ComE (10, 44, 45). In addition to its role in adherence and twitching motility, expression of the ComE pore and Tfp is also required for the uptake of DNA from the extracellular environment (44, 45).

To determine whether the Tfp machinery was perhaps also involved in the release of DNA, we examined an isogenic ∆comE mutant via fluorescence time-lapse microscopy to assess whether this mutant would release DNA into the extracellular environment.

In contrast to the parent, no extracellular fluorescence specific for DNA was observed with the ∆comE mutant, even after an extended incubation time of 6 h (compare Fig. 5A and Movie S3 with Fig. 2A). Interestingly, however, we did observe a subpopulation of cells that appeared to take up the ethidium homodimer-2 DNA stain, as indicated by red fluorescence within the borders of the green fluorescent bacterial outer membranes. The characteristic release of DNA seen with the parent as a red flare that extended beyond the cell membrane (as shown in Fig. 2A) was not observed. This intense red labeling of a subpopulation of ∆comE cells was observed at a later time point (3 h) compared with the parent strain (~1 h until the appearance of a flare) and suggested an accumulation of ethidium homodimer-2 within this subset of cells, likely due to the presence of DNA within the periplasm. Complementation of the comE mutation restored the ability of NTHI to release DNA as a flare and from a subpopulation of cells comparable to that observed for the parental isolate (Figs. 3, green bar and 5B). To confirm that release of DNA and DNABII proteins in this manner was dependent upon expression of the ComE secretin and not another component of the Tfp machinery, we repeated this study with a mutant that could not express the majority subunit of the Tfp, PilA (∆pilA). As shown in Figs. 3, yellow bar and 5C, the ∆pilA mutant released DNA into the environment as did the parental isolate. These results indicated that the subpolar release of DNA and DNABII proteins by NTHI required expression of the ComE pore.

DNA Was Transported Across the NTHI Inner Membrane. To this point, we have described a mechanism by which DNA and DNABII proteins appeared to be released from the bacterial cell into the environment through the ComE outer-membrane pore. However, DNA and DNABII proteins in the cytoplasm must first cross the inner membrane to access the periplasmic space before they can exit the cell. No inner-membrane complex specific for DNA transport has been described in NTHI. However, Neisseria sp. possesses an active T4SS composed of an inner-membrane complex, an outer-membrane complex, and several cytoplasmic chaperone proteins to release ssDNA into the environment for horizontal gene transfer (35). Neisseria shares multiple similarities with NTHI, including noted mosaicism between genomes, despite each organism failing to recognize each other’s uptake signal sequence (46–48). Bioinformatic analysis of the NTHI strain 86-028NP genome identified several genes that are homologous to those of the Neisseria T4SS. NTHI 86-028NP encodes orthologs of the Neisseria inner membrane-spanning proteins TraC and TraG, as well as the cytoplasmic chaperone proteins TraI, ParA, and ParB and the inner membrane-associated protein TraD. Surprisingly, no NTHI genes homologous to those that encode for the outer-membrane portion of the Neisseria T4SS were identified. Because NTHI has no known DNA secretion system and a relatively small conserved genome (1.9 Mb and 1,895 genes), we hypothesized that proteins similar to those of the inner-membrane complex in Neisseria were perhaps nonetheless sufficient to facilitate DNA translocation from the cytoplasm to the periplasm in NTHI. We also reasoned that once in the periplasm, DNA could then be released from the cell through the ComE pore situated within the outer membrane.

To test this hypothesis, we generated a ∆traCG mutant that lacked the predicted inner-membrane proteins TraC and TraG and assessed the ability of this mutant to release DNA into the extracellular environment. Similar to what we observed with the ∆comE mutant, the ∆traCG mutant did not release DNA via the described mechanism (Fig. 6A and Movie S4). Also similar to the ∆comE mutant, there was a minor subpopulation of cells that, over an extended time period, took up the ethidium homodimer-2 DNA stain but, unlike the ∆comE mutant, the stain was now localized to a central area of the cell with a clear demarcation (nonfluorescent,
dark zone) between the green fluorescent outer membrane and the red fluorescence of the DNA, which suggested the presence of DNA within the cytoplasm but not within the periplasm. Complementation of the ΔtraCG mutation restored the DNA release phenotype to similar to that of the parent (Figs. 3, blue bar and 6B). These data suggested that a T4SS outer-membrane complex facilitated the translocation of cytoplasmic DNA across the inner membrane and into the periplasmic space of NTHI.

### Release of DNA from the Cytoplasm into the Extracellular Milieu

**Required Expression of a Tra-Like Inner-Membrane Complex and the ComE Outer-Membrane Pore.** Although no fluorescent flares indicative of a release of DNA to the extracellular milieu were observed by either the ΔcomE or ΔtraCG mutants, fluorescent staining specific for DNA was observed within a subpopulation of both mutants after extended incubation. As introduced above, examination of individual bacterial cells revealed a difference between the ΔcomE and ΔtraCG mutants in the pattern of fluorescent staining seen in the time-lapse videos. Whereas the ΔcomE cells exhibited red fluorescence that was uniformly distributed throughout the bacterial cell, similar fluorescent DNA labeling in the ΔtraCG cells was only present within the central portion of the cell, presumably the cytoplasm (compare Fig. 7B and C). Interestingly, there was a distinct nonfluorescent area that separated the green fluorescent outer membrane and the red fluorescent DNA that was only observed in the ΔtraCG mutant. This nonfluorescent ring suggested an absence of DNA within the periplasm. Collectively, these observations support the hypothesis that TraC and TraG are part of an inner-membrane complex through which DNA is translocated from the cytoplasm to the periplasm for subsequent release into the extracellular environment via the ComE pore.

To confirm the compartmentalization of DNA as we had observed within fluorescently labeled cells (Figs. 7A–C), we now immunolabeled ultrathin sections of parent, ΔcomE, and ΔtraCG cells for dsDNA (using 6-nm colloidal gold) that were then imaged by STEM (Figs. 7D–F). Gold particles were identified by detection of secondary electrons and pseudocolored red in Fig. 7 for ease of interpretation; however, additional images that depict high-contrast secondary electron detection can be seen in Fig. S1. ImmunoSTEM of a 70-nm section of the parent strain showed a subpopulation of bacteria with positive labeling for DNA within the cytoplasm, periplasm, and extracellular milieu (Fig. 7D). Moreover, DNA release appeared to originate from a single location on the bacterial cell with both techniques (compare Fig. 7A and D). The ΔcomE mutant exhibited positive labeling for DNA within the cytoplasm and periplasm; however, no labeling was noted beyond the bacterial outer membrane (Fig. 7E). This observation recapitulated the fluorescent localization observed in the time-lapse microscopy images (Fig. 7B). The distinct ring observed between the outer membrane and fluorescently stained DNA in the ΔtraCG mutant (Fig. 7C) strongly suggested that DNA was confined to the cytoplasm of these cells. This observation was confirmed by immunoSTEM, by which positive labeling for DNA was restricted to the cytoplasm of the ΔtraCG mutant (Fig. 7F).

Collectively, these data further supported our hypothesis that DNA was transferred across the NTHI inner membrane via a T4SS-like Tra complex and across the outer membrane and into the extracellular environment through the ComE pore.

### The Frequency of DNA Release Increased with the Induction of Competence.

Natural competence is defined as the state in which bacteria are capable of being transformed via the uptake of extracellular DNA and is typically induced when bacterial cell densities are high or when bacteria are nutrient-deprived (49–51), as they are when resident within a biofilm (52–57). Because uptake of DNA is increased within biofilms, we hypothesized that this growth phenotype might also be associated with an increased release of DNA by biofilm-resident bacterial cells. To determine whether induction of competence and the release of DNA by biofilm-resident bacterial cells. To determine whether the release of DNA was higher in biofilm-grown bacteria, we quantitated the DNA release events by NTHI. In rich medium (sBHI), we observed an average of 17 events per 1,000 parent cells after 2 h (solid red bar). There were no detectable events for either the ΔcomE or ΔtraCG mutant at this time point. Complementation of the mutations restored the average number of release events similar to that of the parent (compare solid red bar with green, blue, and yellow bars; no statistical differences). Induction of competence by incubation of NTHI in sBHI (red striped bar) increased the number of DNA release events. This increase was statistically significant when NTHI was incubated in M-IV medium (red stippled bar). The number of DNA release events was calculated per 1,000 cells. Data are shown as the mean ± SEM from five separate sets of 1,000 cells (5,000 total cells evaluated). Statistical significance was calculated using one-way ANOVA with significance shown at P ≤ 0.001.

**Fig. 3.** Quantitation of DNA release events by NTHI. In rich medium (sBHI), we observed an average of 17 events per 1,000 parent cells after 2 h (solid red bar). There were no detectable events for either the ΔcomE or ΔtraCG mutant at this time point. Complementation of the mutations restored the average number of release events similar to that of the parent (compare solid red bar with green, blue, and yellow bars; no statistical differences). Induction of competence by incubation of NTHI in sBHI (red striped bar) increased the number of DNA release events. This increase was statistically significant when NTHI was incubated in M-IV medium (red stippled bar). The number of DNA release events was calculated per 1,000 cells. Data are shown as the mean ± SEM from five separate sets of 1,000 cells (5,000 total cells evaluated). Statistical significance was calculated using one-way ANOVA with significance shown at P ≤ 0.001.

- **Parent:** +
- **ΔcomE:** +
- **ΔtraCG:** +
- **ΔpiA:** +
- **sBHI + cAMP:** +
- **M-IV:** +

**Table:**

| Condition       | DNA Release Events per 1,000 Cells |
|-----------------|-----------------------------------|
| Parent          | +                                 |
| ΔcomE           | +                                 |
| ΔtraCG          | +                                 |
| ΔpiA            | +                                 |
| sBHI + cAMP     | +                                 |
| M-IV            | +                                 |

**P Values:**

- **P ≤ 0.001**
To determine whether TraCG was necessary for competence/uptake of DNA from the environment, we conducted transformation efficiency assays with the parental isolate, the ΔtraCG mutant, as well as the complemented ΔtraCG mutant. All isolates demonstrated equivalent competence to the parental isolate (the negative control, ΔcomE, was not competent, as expected) (Fig. S2). These data demonstrated that whereas TraCG facilitated export of DNA and DNABII proteins into the periplasm, it did not appear to be involved in transit of DNA across the inner membrane and into the cytoplasm. To rule out a specific nutritional limitation of the M-IV medium as a cause for the increase in the observed DNA release, given that *H. influenzae* has a strict growth requirement for iron, we assessed NTHI grown in M-IV medium supplemented with heme at the concentration typically used for culture in rich medium, sBHI (2 μg heme per mL). There was no difference in the relative number of bacteria that released DNA when NTHI was grown in M-IV medium supplemented with heme compared with unsupplemented M-IV medium. Therefore this avenue of investigation was not pursued further. These data thus confirmed that the observed increase in DNA release events under competence-inducing conditions was not due to increased cell death as a result of an iron deficiency nor was it likely due to increased biogenesis of outer-membrane vesicles known to occur in *H. influenzae* in response to iron starvation (60). Although competence has long been associated with the uptake of DNA, here we provide evidence that, in NTHI, induction of competence is also associated with the increased release of DNA and likely also the associated DNABII proteins.

**eDNA and DNABII Proteins Released by TraCG and ComE Were Required for the Structure of NTHI Biofilms.** To determine the role of eDNA and DNABII proteins released via TraCG and ComE in the overall architecture of an NTHI biofilm, we assessed biofilms formed by the parent strain, the ΔcomE mutant, and the ΔtraCG mutant for relative biofilm structure as well as for the presence of eDNA and DNABII proteins in the biofilm matrix. Biofilms were grown for 24 h and then labeled for the presence of eDNA and DNABII proteins. The parent strain formed a robust, viable biofilm that contained eDNA and associated DNABII proteins, as expected for these culture conditions (Fig. 8 A, E, and I). In contrast, biofilms formed by both the ΔtraCG and ΔcomE mutants were of significantly reduced height (see each panel for mean biofilm height) and lacked the characteristic shape and architecture of the biofilm formed by the parent strain (Fig. 8 B and C, respectively). In addition, biofilms formed by either mutant had considerably less or no detectable eDNA or DNABII proteins within the biofilm matrix compared with what was observed with the parent strain (compare among Fig. 8 E–G and among Fig. 8 I–K). We attributed the apparent slight increase in labeling for DNA by the ΔtraCG mutant (Fig. 8F) over that by the ΔcomE mutant (Fig. 8G) to the increase in number of adherent cells along the glass surface. Fluorescent staining of the adherent cells resulted in the faint green haze seen in Fig. 8B and can cause some background fluorescence in the light path used to detect DNA. Because the ΔcomE mutant does not express Tfp, a major adhesin, there are fewer individual bacteria adherent to the glass surface to generate similar background labeling. The growth rates of both mutants were similar to that of the parent strain when grown in sBHI and, as such, a growth defect would not account for the observed reduction in biofilm biomass (Fig. S3). The absence of both eDNA and DNABII proteins within the biofilm matrix; both essential for
biofilm structural stability, was reasoned to be responsible for the altered architecture of biofilms formed by the ΔtraCG and ΔcomE mutants.

To further address the importance of DNA and DNABII proteins in the biofilm matrix and provide substantiating evidence that a lack thereof was responsible for the altered architecture and reduced biomass formed by the ΔcomE mutant, we added back both exogenous NTHI DNA and DNABII proteins to the culture system at the time of seeding. This supplementation restored the biofilm height, biomass, and overall architecture to ~50% of that observed with the parental isolate when grown in sBHI (compare Fig. 8D with Fig. 8A). Moreover, both DNA and DNABII proteins were observed within these reconstituted biofilms, as demonstrated by immunolabeling similar to what was observed in parent strain biofilms (compare Fig. 8H and L with Fig. 8E and I, respectively).

**Discussion**

Bacteria within a biofilm are significantly more protected from environmental stresses compared with their planktonic counterparts. The extracellular polymeric substance serves as a semipermeable barrier that protects resident bacteria from both immune effectors and therapeutics such as antibiotics (61, 62). The EPS is composed of a variety of cell-associated and secreted molecules, which include polysaccharides, proteins, lipids, and nucleic acids (63). Extracellular DNA protects bacteria within the biofilm from host defenses via the chelation of antimicrobial peptides and divalent cations (14, 64). In addition, we have shown that eDNA is an important structural component of the biofilm matrix and that the DNABII proteins IHF and HU are required to stabilize the eDNA scaffold that provides structural support to biofilms formed by NTHI and many additional human pathogens (7, 13, 25, 27, 28, 30, 37–39).

There are a number of possible mechanisms that may explain the presence of bacterial DNA in the extracellular environment.
Some bacteria have a mechanism by which a subpopulation of cells will undergo programmed cell death and lysis to release all of their cellular contents into the environment (9). This type of cell lysis provides common goods for neighboring bacteria and releases DNA for horizontal gene transfer (4, 65).

Staphylococcus aureus has been shown to undergo such an altruistic cell death (9). Recently, it was reported that a small proportion of Pseudomonas cells form very large rounded cells that then rapidly undergo explosive cell lysis and release their cellular contents, including DNA, into the extracellular environment (36). In addition, some species such as Neisseria have an active type IV secretion system that transports DNA from the cytoplasm to the extracellular space, presumably for gene transfer (35).

Herein, we identified a mechanism of release of both DNA and DNABII proteins into the environment by a subpopulation of NTHI. To first determine how DNA and DNABII proteins were able to get from within the bounds of the inner membrane and into the periplasm, we analyzed the NTHI genome for potential genes that encode for proteins known to be involved in DNA transport across the inner membrane. Although the genome of NTHI strain 86-028NP lacked orthologs of any of the periplasmic or outer-membrane components found in Neisseria, we did find orthologs of the Neisseria proteins that constitute the T4SS inner-membrane complex. Indeed, work by Juhas and colleagues (66–68) has shown that a novel T4SS, acquired through gene transfer of genomic islands of the ICE Hin 1056 subfamily, is likely the origin of the traC- and traG-like genes found in strain 86-028NP, as well as other NTHI strains. In addition to traC and traG, the genomic island contains genes that encode homologs of the T4SS cytoplasmic chaperone proteins TraI, ParA, and ParB as well as the inner membrane-associated protein TraD. The genomic island of NTHI strain 86-028NP also includes genes involved in excision, integration, replication, and stabilization of integrative and conjugative elements (ICEs) (68).

In the current study, we found that the NTHI TraC and TraG proteins, predicted to form an inner-membrane complex of a...
T4SS, were required for the release of DNA during early biofilm formation. Fluorescence time-lapse microscopy provided evidence to suggest that this complex, similar to that of the Neisseria T4SS inner-membrane complex, actively translocated DNA across the NTHI inner membrane. ImmunoSTEM of cells that could not express either TraC or TraG further confirmed this finding, as no labeling for DNA was observed in the periplasm of any of the cells or in the extracellular space. Although a system similar to the Neisseria T4SS is likely involved in translocation of DNA across the inner membrane, NTHI lacks the components necessary to form a complete T4SS outer-membrane complex. As such, DNA or DNABII proteins transported into the periplasm via the Tra inner-membrane complex would require a heretofore uncharacterized additional mechanism to cross the outer membrane and be released into the extracellular environment.

In data presented here, we show how quickly NTHI releases DNA, with associated DNABII proteins into the extracellular environment, in a lattice-like array of DNA strands. This array is similar to what was observed by Barnes et al. (69) with Enterococcus faecalis, wherein they observed a network of strands of DNA in 4-h cultures by both immunofluorescence and scanning electron microscopy by an as-yet uncharacterized DNA export system. Here, by fluorescence imaging and electron microscopy, we revealed that DNA and DNABII proteins were released from NTHI at a single subpolar location on the cell. The location of this release is consistent with the location of Tfp expression through the ComE pore (44). Unlike the less well-understood mechanism(s) by which NTHI releases DNA into the extracellular milieu, uptake of DNA from the environment is well-studied. Many bacteria, including NTHI and Neisseria, take up DNA from the environment via a process that involves the machinery for expression of type IV pili. NTHI expresses Tfp from a DNA from the environment via a process that involves the machinery for expression of type IV pili. NTHI expresses Tfp from a DNA, with associated DNABII proteins from the periplasmic space into the extracellular environment, in a lattice-like array of DNA strands. This array is known to function in dual processes (70).

Collectively, these observations suggested to us that the ComE pore might be involved in the release of DNA and DNABII proteins from the periplasmic space into the extracellular environment, given that the secretin pore is just wide enough to accommodate a pair of DNA double helices (51). Therefore, we constructed an isogenic comE mutant and found that NTHI that could not express the ComE pore did not release DNA via the mechanism observed with the parent strain. These results suggested that, in addition to the Tra complex that was required for transport of DNA across the inner membrane, the ComE pore was required for the transfer of DNA across the outer membrane. In analysis of the completed genomes of 46 strains of H. influenzae available in the National Center for Biotechnology Information, we found that 25/46 (55%) possessed tra genes whereas 46/46 (100%) had the comE gene. This observation suggests that the majority of NTHI isolates are capable of using this mechanism to release DNA and DNABII proteins into the EPS of their biofilms. Other bacterial secretins are similarly known to function in dual processes (70–72).

A model of the predicted transfer of DNA from the cytoplasm into the periplasm via the Tra inner-membrane complex and then out of the cell via the ComE pore is presented in Fig. 9 (Left). Based on this model, we would predict that a ΔcomE mutant would be able to translocate DNA across the inner membrane via the Tra complex but would be unable to release DNA from the cell due to the absence of the ComE pore (Fig. 9, Center). In a ΔtraCG mutant, DNA would be unable to cross the inner membrane and, as such, no DNA would be present within the periplasmic space or be available to be released by the cell despite the presence of the ComE pore (Fig. 9, Right). This model is supported by our observations of both DNA release by fluorescently labeled whole cells and immunolabeled ultrathin sections of parent, ΔcomE and ΔtraCG cells. Whereas we cannot exclude the possibility that these inner-membrane (TraCG) and outer-membrane (ComE) components form a complex, given the canonical arrangement of the type IV pilus machinery, which does indeed require linkage of its own inner- and outer-membrane components both spatially and temporally, we do not currently favor this possibility. Further, we do not yet know whether the described method of release of both DNA and
DNAII into the extracellular milieu requires adherence of NTHI to a substratum or not; however, this is the subject of ongoing investigation.

Diseases caused by NTHI are often chronic and recurrent in nature due to the formation of highly recalcitrant biofilms. Extracellular DNA and DNAII proteins are required for biofilm structure and stability. The targeted removal of eDNA and/or DNAII proteins has been shown to cause catastrophic biofilm collapse in vitro and disruption of biofilms in three distinct animal models of disease induced by three important human pathogens of the middle ear, oral cavity, and lung (13, 26, 29). Here we show that release of DNA and DNAII proteins via a mechanism that involves both the Tra inner-membrane complex and the ComE pore is critical for biofilm formation in vitro. Biofilms formed in vitro by bacteria unable to release DNA and DNAII proteins via this mechanism lacked extracellular DNA and DNAII proteins in the biofilm matrix, which resulted in a compromised and atypical biofilm architecture. This mechanism of release of both DNA and DNAII proteins is therefore likely critical to biofilm stability in vivo as well.

Naturally competent bacteria can take up foreign DNA from the environment via a two-step process that involves both transfer of DNA from the bacterial surface to the cytoplasmic membrane and translocation of DNA across the cytoplasmic membrane that may or may not be spatially and temporally coupled (73, 74). There is a relationship between cell growth and development of competence in NTHI (58), wherein a greater cell density with slow growth, as in a biofilm, increases competence. We have shown that induction of competence also modestly increased the number of NTHI within a population that released DNA and DNAII proteins. We surmise that this increase was limited due to the state of competence, which induced comE expression but not concomitant expression of traCG. This outcome resulted in the rate-limiting step being the transit of DNA through the inner membrane into the periplasm. Importantly, other genera demonstrate a similar DNA release phenotype induced by competence. Streptococcus pneumoniae can trigger cell lysis of neighboring bacteria of the same species (fratricide) and DNA release when competence is induced (75). A relationship between competence and eDNA has also been shown in Neisseria gonorrhoeae (76), Pseudomonas stutzeri (77), and Bacillus subtilis (78). However, to the best of our knowledge, the induction of competence has heretofore not been associated with the release of DNA by NTHI.

Herein, we described a mechanism by which NTHI releases DNA and DNAII proteins into the environment that is independent of explosive cell lysis. We have shown that DNA appeared to transit from the cytoplasmic space to the periplasm via a T4SS-like inner-membrane complex and was then released, along with DNAII proteins, into the environment through the ComE outer-membrane pore. Taken together, these data indicated that this TraCG- and ComE-dependent mechanism of release is critical for NTHI biofilm formation. These findings describe a mechanism by which a subset of NTHI released DNA and DNAII proteins into the extracellular milieu, where they are known to provide structural support to the biofilm, which protects resident bacteria. Knowledge of the mechanism and kinetics of release of DNA and DNAII proteins can be integrated into our development of biofilm-targeted disruption and prevention strategies.

Materials and Methods

NTHI strain 86-028NP is a low-passage clinical isolate. NTHI was maintained as frozen stocks and cultured on chocolate agar (Remel) at 37 °C with 5% CO2 for 18 to 20 h before use. A ComE deletion mutant (∆comE) and its complement (ComE) were described previously (44). A TraCG mutant (∆traCG) was generated by replacement of the traCG region of the chromosome with a kanamycin resistance cassette. Briefly, regions ~1 kb upstream and downstream of the traCG region were amplified by PCR and ligated with SphI and EcoRI, respectively. The flanking regions were then ligated to a kanamycin resistance cassette that had been amplified by PCR from pMLN1-7 (79) and digested with SphI and EcoRI. NTHI strain 86-028NP was transformed with the resultant DNA fragment using a modified MIV transformation protocol (80, 81). Transformants were selected on chocolate agar supplemented with kanamycin (20 μg/ml) and sequenced to verify allelic exchange.

The ΔtraCG mutant was complemented via use of a derivative of pSPEC1 (44) that contained the traCG genes. Briefly, the traCG region of NTHI strain 86-028NP was amplified by PCR, digested with Ncol and PvuI, and ligated into pSPEC1 that had been digested with Ncol and PvuI. The resultant plasmid, pJA1, was confirmed by sequencing and used to transform the ΔtraCG mutant via electroporation. All PCR assays were performed with Q5 high-fidelity DNA polymerase (New England Biolabs). All restriction enzymes were purchased from New England Biolabs.

To demonstrate the singular subpolular location of expression of ComE, the com locus from NTHI strain 86-028NP was amplified from genomic DNA by PCR using a forward primer containing a BglII site and a reverse primer that encodes a FLAG epitope tag and an EcoRI site. The product was digested with BglII and EcoRI and ligated with pCLOADuet-1 (EMD Millipore) previously digested with BamHI and EcoRI and transformed into ElectroMAX Escherichia coli DH5α (Thermo Fisher Scientific), and transformants were selected onuria agar containing 20 μg kanamycin per ml. Isolated plasmids were confirmed by restriction analysis and sequencing and then transformed into E. coli BL21 Star (DE3) (Thermo Fisher Scientific). Transformants were again selected onuria agar containing 20 μg kanamycin per ml.

Detailed materials and methods can be found in SI Materials and Methods.

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1. Murphy TF, Bakaleza LO, SMEesters PR (2009) Microbial interactions in the respiratory tract. Pediatr Infect Dis J 28:10–S11.
2. H unstad DA, Justice SS (2010) Intracellular lifestyles and immune evasion strategies of uropathogenic Escherichia coli. Annu Rev Microbiol 64:203–221.
3. Bakaleza LO (2012) Bacterial biofilms in the upper airways—Evidence for role in pathology and implications for treatment of otitis media. Paediatr Respir Rev 13:154–159.
4. Payne DE, Boles BR (2016) Emerging interactions between matrix components during biofilm development. Curr Genet 62:137–141.
5. Whitchurch CB, Tolker-Nielsen T, Raga PC, Mattick JS (2002) Extracellular DNA required for bacterial biofilm formation. Science 295:1487.
6. Hall-Stoodley L, et al. (2008) Characterization of biofilm matrix, degradation by DNase treatment and evidence of capsule downregulation in Streptococcus pneumoniae clinical isolates. BMC Microbiol 8:173.
7. Jurcisek JA, Bakaleza LO (2007) Biofilms formed by nontypeable Haemophilus influenzae in vivo contain both double-stranded DNA and type IV pilin protein. J Bacteriol 189:3686–3687.
8. Mosco M, Garcia E, Lopez R (2006) Biofilm formation by Streptococcus pneumoniae. Role of choline, extracellular DNA, and capsular polysaccharide in microbial adhesion. J Bacteriol 188:7785–7795.
9. Qin Z, et al. (2007) Role of autolysin-mediated DNA release in biofilm formation of Staphylococcus epidermidis. Microbiology 153:2083–2092.
10. Jurcisek JA, et al. (2007) The PilA protein of non-typeable Haemophilus influenzae plays a role in biofilm formation, adherence to epithelial cells and colonization of the mammalian upper respiratory tract. Mol Microbiol 65:1288–1299.
11. Izano EA, Amarante MA, Kher WB, Kaplan JB (2008) Differential roles of poly-N-acetylmuramic acid surface polysaccharide and extracellular DNA in Staphylococcus aureus and Staphylococcus epidermidis biofilms. Appl Environ Microbiol 74:470–476.
12. Thomas VC, Thurlow LR, Boyle D, Hancock RE (2008) Regulation of autolysis-dependent extracellular DNA release by Enterococcus faecalis extracellular proteases influences biofilm development. J Bacteriol 190:5690–5698.
13. Goodman SD, et al. (2011) Biofilms can be dispersed by focusing the immune system on a common family of bacterial nucleoid-associated proteins. Mucosal Immunol 4:625–637.
14. Jones EA, Mc Gillivray G, Bakaleza LO (2013) Extracellular DNA within a nontypeable Haemophilus influenzae-induced biofilm binds human beta-defensin-3 and reduces its antimicrobial activity. J Innate Immune 5:24–38.
15. Mulcahy H, Charron-Mazened L, Levenza S (2008) Extracellular DNA chelates cations and induces antibiotic resistance in Pseudomonas aeruginosa biofilms. PLoS Pathog 4:e1000213.
16. Haddad J, Furmelle M, Hansen LH, Srensen SJ (2011) The interconnection between biofilm formation and horizontal gene transfer. FEMS Immunol Med Microbiol 63:183–195.
17. Molin S, Tolker-Nielsen T (2003) Gene transfer occurs with enhanced efficiency in biofilms and induces enhanced stabilization of the biofilm structure. Curr Opin Biotechnol 14:255–261.
18. Goodman SD, Nash HA (1989) Functional replacement of a protein-induced bend in a DNA recombination site. Nature 341:251–254.
