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# Autolysin-Independent DNA Release in Streptococcus pneumoniae Invitro Biofilms

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**Abstract**

Microbial biofilms provide an appropriate environment for increased genetic exchange. Extracellular DNA (eDNA) is an essential component of the extracellular matrix of microbial biofilms, but the pathway(s) responsible for DNA release are largely unknown. Autolysis (either spontaneous or phage-induced) has been proposed the major event leading to the appearance of eDNA. The 'suicidal tendency' of *Streptococcus pneumoniae* is well-known, with lysis mainly caused by the triggering of LytA, the major autolytic amidase. However, the LytC lysozyme and CbpD (a possible murein hydrolase) have also been shown involved. The present work examines the relationship between eDNA, autolysins, and the formation and maintenance of *in vitro* pneumococcal biofilms, via fluorescent labeling combined with confocal laser scanning microscopy, plus genetic transformation experiments. Bacterial DNA release mechanisms other than those entailing lytic enzymes were shown to be involved by demonstrating that horizontal gene transfer in biofilms takes place even in the absence of detectable autolytic activity. Evidence that the release of DNA is somehow linked to the production of extracellular vesicles by *S. pneumoniae* is provided.

**Keywords:** Pneumococcus; *Streptococcus pneumoniae*; Extracellular DNA; Biofilms; Autolysins

## Introduction

The human pathogen *Streptococcus pneumoniae* is a leading cause of pneumonia, meningitis and bloodstream infections in the elderly, and one of the main pathogens responsible for middle ear infections in children. It is carried asymptomatically in the nasopharynx of many healthy adults, and in as many as 20–40% of healthy children. Pneumococcal biofilms appear on adenoid and mucosal epithelium in children with recurrent middle-ear infections and otitis media with effusion, and on the sinus mucosa of patients with chronic rhinosinusitis, and they can be also formed *in vitro* [1,2]. Interestingly, biofilm-grown pneumococci have distinct transcriptional profiles compared to planktonic cells [2,3]. Biofilm formation in *S. pneumoniae* is an efficient way of evading both the classical and the *PspC*-dependent alternative complement pathways [4].

Over 60% of all human bacterial infections, and up to 80% of those that become chronic, are thought to involve growth in biofilms. A biofilm is defined as an accumulation of microorganisms embedded in a self-produced extracellular matrix (ECM) adhered to an abiotic or living surface. The ECM is composed of different polymers, mainly polysaccharides, proteins, and nucleic acids. The requirement of extracellular deoxyribonucleic acid (eDNA) in ECM formation and maintenance has been documented in a variety of Gram-positive and Gram-negative bacteria [5]. eDNA binds to polysaccharides and/or proteins, protecting bacterial cells from physical and/or chemical challenges [6], as well as providing biofilms with structural integrity. It is a major component of the *S. pneumoniae* ECM [7–9]. Various pneumococcal surface proteins, *e.g.,* several members of the choline-binding family of proteins (CBPs) [9,10], and the pneumococcal serine-rich repeat protein (PsrP) [11] form tight complexes with eDNA via electrostatic interactions. It should be noted that PsrP appears in ≈ 60% of clinical pneumococcal isolates, whereas the main CBPs — LytA, LytB, LytC or CbpD among others — are present in all *S. pneumoniae* strains.

The source of eDNA may vary across microorganisms and in part appears because of autolysis, phage-induced lysis, and/or active secretion systems, as well as through association with extracellular vesicles (EV). In *S. pneumoniae*, the release of DNA during limited lysis of the culture, *i.e.,* by controlled autolysis directed by the main CBP autolysins (LytA *N*-acetylmuramoyl-L-alanine amidase [NAM-amidase] and LytC lysozyme), as well as prophage-mediated lysis, have been proposed as biofilm-promoting in part of the bacterial population [9,12]. The NAM-amidase LytA, the main autolytic enzyme of *S. pneumoniae*, is kept under control by lipoteichoic acid — (a membrane-bound teichoic acid that contains choline) — during exponential growth, and regulated at the level of substrate recognition [13]. LytC also acts as an autolysin when pneumococci are incubated at about 30°C, a temperature close to that of the upper respiratory tract [14]; this lysozyme might be post-transcriptionally inhibited by CbpF [15].

Studies in different microorganisms suggest that the appearance of eDNA in biofilms may also be a response to the accumulation of quorum sensing (QS – a cell density-dependent communication system that regulates cooperative behavior) signals [16]. Early studies on genetic transformation in planktonic cultures showed *S. pneumoniae* to release measurable amounts of DNA in the absence of detectable autolysis [17]. Although these pioneering studies were forgotten for years, more recent investigations have shown that LytA, LytC and CbpD (a putative

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cell wall-degrading enzyme) are directly responsible for autolytic DNA release from only a subset of cells in competent pneumococcal planktonic cultures [18]. In fact, the killing of non-competent sister cells by competent pneumococci — a phenomenon named fratricide — promotes allolysis and DNA release [19].

It is well known that competence induction in *S. pneumoniae* depends on a QS mechanism. LytA, LytC and CbpD are all required for allolysis (and for the concomitant DNA release) when pneumococci grow under planktonic conditions [20]. It is currently believed that the limited damage caused by CbpD activates LytA and LytC, resulting in the more extensive lysis of target cells than that achieved by CbpD alone. LytA and LytC are constitutively synthesized by non-competent cells. However, while the expression of LytA increases during competence, LytC is not part of the competence regulon in *S. pneumoniae* [21]. A slightly different situation has been proposed to occur in biofilms. The lysis of target (non-competent) cells in biofilms requires CbpD to act in conjunction with LytC, whereas LytA is not required for efficient fratricide-mediated gene exchange [21]. In these experiments, however, a direct visualization of eDNA in the ECM was not reported. Interestingly, the transcription of both *lytA* and *cbpD* also appears to be regulated by the LuxS/autoinducer-2 (AI-2) QS [22].

Via the use of an *in vitro* biofilm model system, the present work provides evidence that a small (but significant) proportion of biologically active, eDNA in pneumococcal biofilms is released into the medium by an alternative (or complementary) pathway to cell autolysis. It would appear that this occurs independent of the activity of LytA, LytC and CbpD and the QS systems (ComABCDE and LuxS/AI).

## Materials and Methods

### Strains, media and growth conditions

Table S1 (Supporting Information) lists the pneumococcal strains used in this study; all were grown in pH 8-adjusted C medium (CpH8) supplemented with 0.08% yeast extract (C+Y) medium, or not, as required [7]. Cells were incubated at 37C without shaking, and growth monitored by measuring absorbance at 550 nm ($A_{550}$). When used, antibiotics were added at the following concentrations: erythromycin 0.5 μg mL$^{-1}$, kanamycin 250 μg mL$^{-1}$, novobiocin (Nov) 10 μg mL$^{-1}$, optochin (Opt) 5 μg mL$^{-1}$, tetracycline 1 μg mL$^{-1}$, spectinomycin (Spc) 100 μg mL$^{-1}$, and streptomycin (Str) 100 μg mL$^{-1}$. DNase I (from bovine pancreas, DN25) was purchased from Sigma-Aldrich. For the construction of mutants (Table S1, Supporting Information), the appropriate *S. pneumoniae* strains were transformed with chromosomal or plasmid DNA in C medium supplemented with 0.08% bovine serum albumin after treating cells with 250 ng mL$^{-1}$ synthetic CSP-1 at 37°C for 10 min to induce competence, followed by incubation at 30°C during DNA uptake.

Biofilm formation was determined by the ability of cells to adhere to the walls and base of 96-well (flat-bottomed) polystyrene microtiter dishes (Costar 3595; Corning Incorporated) [23]. Unless stated otherwise, cells grown in C+Y medium to an $A_{550}$ of 0.5–0.6, sedimented by centrifugation, resuspended in an equal volume of the indicated pre-warmed medium, diluted 1/10 or 1/100, and then dispensed at a concentration of 200 μl per well. Plates were incubated at 34°C for 3, 4.5 and 5 h and bacterial growth determined by measuring the $A_{595}$ using a VersaMax microplate absorbance reader (Molecular Devices). The biofilm formed was stained with 1% crystal violet [23].

### Intrabiofilm gene transfer

Exponentially growing cultures of donor strains (see above) were seeded together in a 1:1 ratio in polystyrene microtiter plates and incubated in C+Y medium at 34°C. Previous results have indicated that biofilm-grown pneumococcal cells must be actively growing to become competent [21]. Hence, biofilms formation was allowed for only 4.5 h; non-adherent cells were removed and adherent cells were washed with PBS, disaggregated by gentle pipetting and slow vortexing [4]. The latter were then serially diluted and plated on blood agar plates containing Nov plus Str. Nov$^r$ Str$^r$ transformants were then picked from plates containing Opt to ascertain their parental strain. For each donor strain the total number of viable cells was determined using blood agar plates containing either Nov or Opt plus Str.

### Preparation of extracellular vesicles and microscopical examination.

EV-enriched centrifugation fractions were prepared from S. pneumoniae following standard procedures [24]. Briefly, for biofilms, one liter of C+Y medium was inoculated with 10 mL of an exponentially growing culture of strain P271, distributed in 50 Petri dishes (10 cm diameter), and incubated at 34°C for 4.5 h. The non-adherent cells in the dishes were pipetted off and the biofilm-growing cells (6–7 × 10$^9$ CFU) suspended in 75 mL of fresh C+Y medium. After centrifugation (9500 × g, 20 min, 4°C) the supernatant was filtered through a 0.2 μm pore-size filter (Millipore). The filtrate was centrifuged at 100 000 × g for 1 h at 4°C to sediment the vesicular fraction into a pellet. The supernatant was then discarded and the pellet suspended in a small volume of C+Y medium (EV fraction) and stored in aliquots at –20°C. Aliquots of the EV fraction were also treated with DNase I (10 μg mL–1) for 1 h at 37°C. EDTA (50 mM), SDS (1%) and proteinase K (100 μg mL–1) were then added and the mixtures incubated for 2 h at 37°C. Extraction was performed with phenol, and precipitation with ethanol, following standard procedures. Finally, the pellet was dissolved in a small volume of 10 mM Tris-HCl, pH 8.0 containing 1 mM EDTA. Cultures of the same pneumococcal strain were also grown under planktonic conditions until late exponential phase (≈ 3 × 10$^8$ CFU mL$^{-1}$) at 37°C without agitation, and processed as biofilm-grown pneumococci for EV preparation.

EV preparations (7 μL) were spotted on a glass slide, air dried, stained with the red fluorescence, membrane dye FM 4-64 (Molecular Probes), and incubated with α-dsDNA (ab27156, Abcam) followed by incubation with Alexa fluor 488-labeled goat anti-mouse IgG (A-11001, Invitrogen) (see below). Specimens were observed under a Leica DM4000B fluorescence microscope and viewed under a Leica HC PL APO63 × /1.40–0.60 oil objective. S. pneumoniae P271 biofilms formed on glass surfaces were prepared for low-temperature scanning electron microscopy (LTSEM) as previously described (Moscoso et al. 2006), and observed at –135°C using a DSM 960 Zeiss scanning electron microscope. For transmission electron microscopy (TEM) analysis, 5 μL of EV were placed for 5 min at room temperature on carbon-reinforced, Formvar-coated copper grids (300 mesh), which had been rendered hydrophilic by glow-discharge using a Quorum GloQube apparatus (Quorum Technologies). The sample was quickly washed with ultrapure water and negative staining was performed using 1% sodium phosphotungstate for 5 min. The excess stain was removed, and the sample was allowed to dry. Micrographs were taken on a JEOL JEM 1230 working at 80 kV.

### Quantification of eDNA

DNA quantification was performed by spectrophotometry (with concentrated samples) and/or using genetic transformation experiments [25]. It is well known that a first-order concentration

dependence (near unity) exists in chromosomal DNA transformation in pneumococci and other bacteria. This was confirmed in this study (see Figure S1, Supporting Information). It should be underlined that, since the size of the S. pneumoniae R6 genome is about 2 Mb, the DNA content of a single CFU, i.e., a diplococcus, equals approximately 4 fg.

### Microscopic observation of biofilms

For the observation of S. pneumoniae biofilms by the confocal laser scanning microscope (CLSM), pneumococcal strains were grown on glass-bottomed dishes (WillCo-dish) for 3–5 h at 34°C as previously described [9]. Following incubation, the culture medium was removed and the biofilm rinsed with phosphate-buffered saline (PBS) to remove non-adherent bacteria. The biofilms were then stained with DDAO (7-hydroxy-9H-[1,3-dichloro-9,9-dimethylacridin-2-one) (2 μM) (H6482, Invitrogen), anti-double-stranded (ds) DNA monoclonal antibodies (α-dsDNA) (at 2–25 μg mL–1 each) and/or SYTO 59 (10 μM) (S11341, Invitrogen). All staining procedures involved incubation for 10–20 min at room temperature in the dark, except when biofilms were incubated with mouse α-dsDNA (2 μg mL–1); this involved a fixation step at room temperature with 3% paraformaldehyde for 10 min. The biofilms were then rinsed with 0.5 mL PBS and incubated for 1 h at 4°C followed by 30 min incubation at room temperature in the dark with Alexa fluor 488-labeled goat anti-mouse IgG (1:500). After staining, the biofilms were gently rinsed with 0.5 mL PBS. Observations were made at a magnification of 63× using a Leica TCS-SP2-AOBS-UV or TCS-SP5-AOBS-UV CLSM equipped with an argon ion laser. Laser intensity and gain were kept the same for all images. Images were analyzed using LCS software from Leica. Projections were obtained in the *x–y* (individual scans at 0.5–1 μm intervals) and *x–z* (images at 5–6 μm intervals) planes.

### Statistical analysis

Data comparisons were performed using the two-tailed Student *t*-test. A P value of $< 0.05$ was considered statistically significant.

## Results

### Visualization of eDNA in the pneumococcal biofilm

S. pneumoniae R6 biofilms grown for 5 h at 34°C in C+Y medium were stained with a combination of SYTO 59, DDAO and α-dsDNA. When examined under the CLSM, abundant, mostly cell-associated eDNA was observed (Figure 1). However, when scanned at 488 nm (green), immunostained eDNA appeared as a lattice-like array consisting of long DNA fibers, mainly at the top of the biofilm (Figure 1C). Only seldomly they were associated with the cocci (marked with yellow arrows in Figure 1I). At the bottom of the biofilm, small areas of what appeared to be compacted eDNA (but no fibers) were seen (data not shown).

Notably, DNA fibers were not observed when DDAO was employed. Many reports have used DDAO for staining eDNA in biofilms [26]. However, a recent evaluation of eDNA stains in biofilms of various species has shown that this compound was neither completely cell impermeant nor capable to reveal DNA-containing fibrilar structures [27]. As our results were in agreement with these data, DDAO was not used in additional experiments.

To study the dynamics of eDNA release, strain R6 was incubated under biofilm-forming conditions for up to 5 h at 34°C. Immunostaining with α-dsDNA of sessile (adherent) cells revealed the existence of eDNA even at early incubation times (Figure 2). At 3 h, eDNA filaments were visible, although the majority of eDNA appeared as dots and patches, which may represent different stages of condensation of DNA–protein aggregates, as previously suggested [10]. In 5 h-old biofilms, eDNA threads were infrequent and mainly located at the top of the biofilm (see above). Previous studies have revealed the existence of a mature

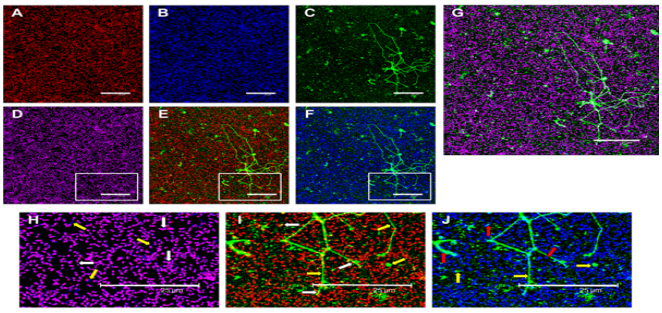


**Figure 1:** Evidence of the existence of eDNA in pneumococcal biofilms using CLSM. A biofilm of *S. pneumoniae* R6 grown for 5 h at 34ºC in C+Y medium was stained with a combination of SYTO 59 (A, red), DDAO (B, blue), and α-dsDNA, followed by Alexa Fluor-488 goat anti-mouse IgG (C, green). Image D is a merge of channels A and B. Image E is a merge of channels A and C. Image F is a merge of channels B and C. Image G is a merge of the three channels. Images H, I and J correspond, respectively, to an enlarged vision of the area marked with squares in D, E and F. Yellow arrows point to eDNA stained only with DDAO or α-dsDNA–Alexa Fluor-488. White arrows indicate the location of SYTO 59-stained bacteria together with eDNA labeled either with DDAO (H, magenta) or with α-dsDNA–Alexa Fluor-488 (I, yellow). The red arrow in image J points to doubly labeled (DDAO plus α-dsDNA–Alexa Fluor- 488) eDNA (J, light blue). Scale bars = 25 μm.

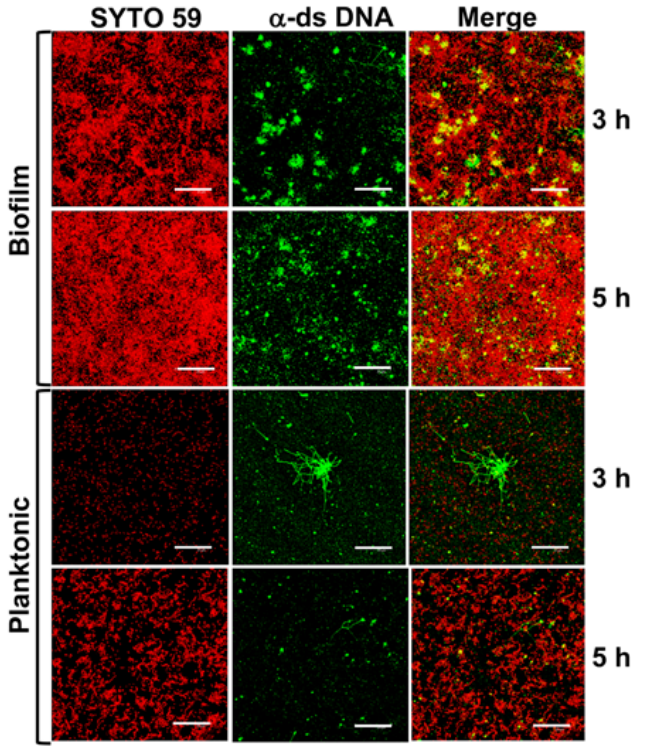


**Figure 2:** Dynamics of eDNA release in pneumococcal biofilms. S. pneumoniae R6 was grown under biofilm-forming conditions. After 3 and 5 h incubation at 34ºC, adherent (biofilm) and non-adherent (planktonic) cells were independently stained with a combination of SYTO 59 (red) and α-dsDNA–Alexa Fluor-488 (green). Scale bars=25 μm.

ECM (consisting of DNA, proteins and polysaccharides) at this time point [9]. Immunostaining planktonic cultures (i.e., non-adherent cells) revealed the existence of eDNA filaments that were more abundant in younger than in older cultures (Figure 2).

## Evidence of the presence of eDNA in biofilms formed by different pneumococcal mutants

The involvement of eDNA in biofilm formation and maintenance was ascertained using strain P046, which lacks the two main autolytic CBPs. Strain P234 was employed as a control; this has a point mutation in the *pspC* (= *cbpA*) gene, which encodes a CBP important in virulence. *PspC*, which lacks any autolytic activity and is partly involved in biofilm formation *in vitro* (on polystyrene microtiter plates) [7], and in vivo (in a murine nasopharynx colonization model) [2], also forms complexes with the eDNA [10]. Compared to the parental R6 strain, both mutants showed reduced biofilm-forming capacity, in agreement with previous findings [7]. Interestingly, biofilm formation, but not culture growth, was greatly impaired when pneumococci were grown in the presence of DNase I (Figure 3). Moreover, the incubation of preformed biofilms with DNase I drastically diminished the number of biofilm-associated sessile cells. As a whole, however, preformed biofilms were less reduced by DNase I treatment than growing biofilms, strongly suggesting that eDNA is more important and/or more exposed during the early stages of biofilm formation. Alternatively, eDNA may become resistant to DNase enzymes during biofilm maturation by forming complexes with other macromolecules such as CBPs.

The presence of eDNA in the biofilms of Δ*comC* or Δ*luxS* mutants was also analyzed. These genes are essential for the functioning of two QS systems documented as being involved in biofilm formation (see above). The *comC* gene codes for the pre-CSP (competence-stimulating peptide), which is matured and exported by the ComA–ComB complex as an unmodified 17-residue-long peptide pheromone. LuxS is an S ribosylhomocysteine lyase, and is responsible for the production of the QS molecule homoserine lactone autoinducer 2 (AI-2). It has been reported that transcription of competence genes (including *lytA* and *cbpD*) is reduced in a ΔluxS strain [22]. As shown above for two CBP mutants, the Δ*comC* and Δ*luxS* mutants produced only ≈50% of the biofilm formed by the R6 strain (Figure 3). Positive evidence for the involvement of eDNA in formation and maintenance of these biofilms was also obtained by treatment with DNase I (Figure 3).

## Contribution of lytic CBPs to eDNA reléase

The presence of eDNA in the ECM of biofilms formed by strain P046 — a double LytA$^-$ LytC$^-$ mutant — was unexpected since it is generally believed that at least one of the autolysins is required for DNA release (see above). To gain further insight, the existence of eDNA in the biofilm formed by a mutant deficient in CbpD (or its combination with the *lytA* and *lytC* mutations) was analyzed. A *pspC* mutant (strain P234) was included as a control. Notably, eDNA was present even in the ECM of strain P204, a mutant deficient in the three CBPs, i.e., LytA

LytC and CbpD (Figure 4). The morphology of the biofilms formed by strain P204 differed from those of R6, with the former biofilms containing fewer microcolonies and larger eDNA patches than the wild type.

It is well known that when pneumococcal cells are incubated with 2% choline chloride, CBPs are released into the medium. Those with enzymatic activity are completely inhibited, but transformability is not altered. Under these conditions, however, the biofilm-forming capacity is severely reduced [7]. This was confirmed in the present work, and might be attributed (at least in part) to the drastically diminished

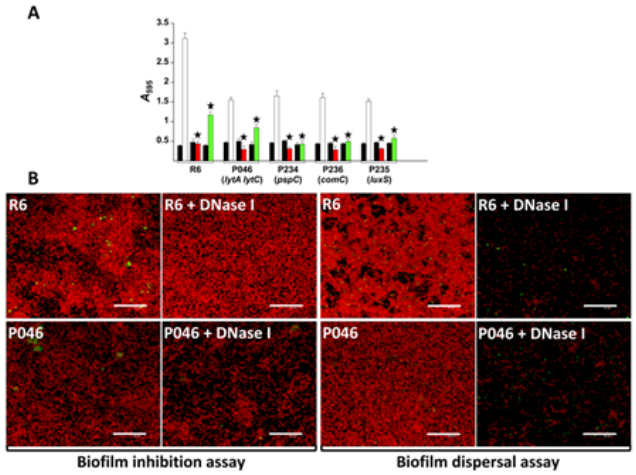


**Figure 3:** Inhibition and dispersal of pneumococcal biofilms with DNase I. (A) The indicated S. pneumoniae strains were grown overnight at 37ºC to an $A_{550}$ value of 0.5 (corresponding to the late exponential phase of growth) in C+Y medium, centrifuged, and adjusted to an $A_{550}$ of 0.6 with fresh medium. The cell suspensions were then diluted 100-fold, and 200 µL aliquots distributed into the wells of microtiter plates, which were then incubated for 5 h at 34ºC (open bars). Other samples received DNase I (100 µg mL$^{-1}$) (red bars) and were incubated as above (inhibition assay). (B) In other cases, and after biofilm development (4 h at 34ºC), DNase I (green bars) was added at 100 µg mL$^{-1}$, and incubation allowed to proceed for an additional 1 h at 34ºC before staining with CV to quantify biofilm formation (dispersal assay). In all assays, black bars indicate growth (adherent plus non-adherent cells). *, P<0.001 compared with the corresponding, untreated control.

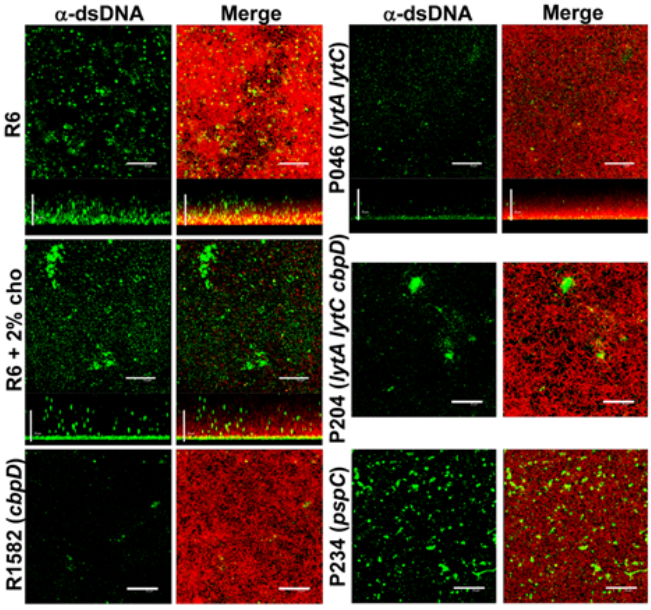


**Figure 4:** Influence of autolysins on biofilm formation and eDNA release revealed by CLSM. Biofilms were stained with a combination of SYTO 59 (red), and α-dsDNA, followed by Alexa Fluor-488 goat anti-mouse IgG (green). The R6 strain was also incubated in C+Y medium containing 2% choline chloride (R6+2% cho). Horizontal and vertical three-dimensional reconstructions of 55 (*x*–*y* plane) or 65 scans (*x*–*z* plane) are shown. Scale bars=25 µm.

eDNA content of the biofilm. Quite unexpectedly, R6 biofilms formed in the presence of 2% choline chloride still showed the presence of eDNA (Figure 4).

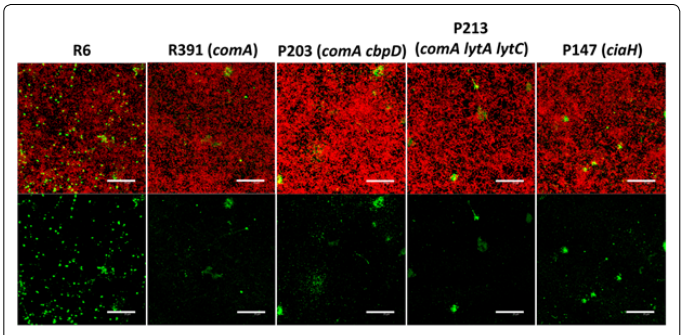


**Figure 5:** Influence of competence induction on biofilm formation and eDNA release revealed by CLSM. Biofilms were stained with a combination of SYTO 59 (red), and α-dsDNA, followed by Alexa Fluor-488 goat anti-mouse IgG (green). Scale bars = 25 μm.

## The competence QS system is not involved in eDNA reléase

The presence of eDNA in biofilms formed by additional S. pneumoniae strains possessing combinations of mutations affecting the comA gene and various lytic genes was studied by CLSM. These strains were R391, P203, P204, and P213. The P147 strain ($ciaH_{Tupelo\_VT}$) was also included since in previous work our group has shown that CiaR/H, a two-component signal transduction system that mediates the stress response, is in some way: a) implicated in the triggering of the LytA autolysin [28], b) required for efficient *in vitro* biofilm formation and nasopharyngeal colonization in a mouse model [29], and c) involved in the control of competence for genetic transformation [30]. CLSM observations of *in vitro* biofilms showed eDNA to be also present in the biofilms of every mutant tested (Figure 5).

## Transforming capacity of eDNA in pneumococcal biofilms

The above results indicate that *in vitro* pneumococcal biofilms are capable of releasing eDNA in a manner apparently independent of the activity of the three pneumococcal autolysins LytA, LytC and CbpD — even though these were generally believed necessary for DNA release in planktonic cultures. To investigate whether the eDNA in the biofilms formed by pneumococci simultaneously deficient in these three lytic enzymes has transforming activity, the efficacy of gene transfer in mixed biofilms was determined. For this, the reciprocal (donor and recipient) transforming capacity of two strain pairs was measured: in addition to being autolysin proficient (or not), one pair harbored the well-known low efficiency (LE) *nov1* marker (a C:G to T:A transition mutation conferring Nov resistance), and the other the high efficiency (HE) marker *str41* (an A:T to C:G transversion), which bestows streptomycin resistance. To allow for further characterization of the direction of DNA transfer, the latter pair of strains used was also resistant to Opt. In pneumococcal transformation, the LE markers return 5–10% as many transformed cells as do HE markers (which are little degraded, or not at all). Table 1 shows that, in the biofilms, the spontaneous transformation of autolysin-proficient strains (P233 and P273) took place at levels typically observed in planktonic cultures when using naked chromosomal DNA (between 0.1 and 1% of total viable cells). Moreover, the heteroduplex DNA base mismatch repair system (Hex), which is responsible for marker-specific variations in transforming efficiency in planktonic cultures [31], was functional in the pneumococcal biofilms, as deduced from the relative transfer efficiency of the LE *nov1* and HE *str41* mutations (Table 1). In agreement with that reported by other authors [21], the transformation frequency was reduced by more than 100-fold in mixed biofilms formed by the mutants deficient in the three lytic enzymes. On average, however,

| Strain | | Transformation frequency[b] | |
|---|---|---|---|
| | | Str$^r$ | Nov$^r$ |
| P233 (Nov$^r$) | P273 (Opt$^r$ Str$^r$) | 0.45 ± 0.10 | 0.04 ± 0.02 |
| P272 (*lytA lytC cbpD* Nov$^r$) | P271 (*lytA lytC cbpD* Opt$^r$ Str$^r$) | $0.27 \times 10^{-2} \pm 0.05 \times 10^{-2}$ | $0.30 \times 10^{-3} \pm 0.19 \times 10^{-3}$ |

**Table 1:** Transformation efficiency in *S. pneumoniae* biofilms[a].

| DNA origin | Total DNA content (μg) | Cell equivalents (%) |
|---|---|---|
| Biofilm | | |
| Intracellular | 65 | $1.6 \times 10^{10}$ (100) |
| EV-associated | $7.5 \times 10^{-5}$ | $1.9 \times 10^{4}$ (0.00012) |
| EV-associated + DNase I | ND | – |
| Planktonic culture | | |
| Intracellular | $3 \times 10^{3}$ | $7.5 \times 10^{11}$ (100) |
| EV-associated | $1.2 \times 10^{-2}$ | $3 \times 10^{6}$ (0.0004) |
| EV-associated + DNase I | ND | – |

**Table 2:** Transforming eDNA in pneumococcal biofilms and planktonic cultures[a].

one among $10^5$ pneumococci showed transformation to streptomycin resistance, demonstrating that a small amount of biologically active eDNA was still present in the ECM of the biofilms formed by the triple deficient mutant.

Previous studies performed with different bacteria have suggested that, in addition to autolytic phenomena, eDNA might be associated with EV. Recent evidence indicates that S. pneumoniae, actively sheds extracellular nano-sized EV, as do many other microorganisms [32]. Whether pneumococcal EV contains DNA, however, was never examined. Here, high-speed sediments of biofilm filtrates — a crude preparation of EV with associated DNA (see Figure S2, Supporting Information) — were used to perform additional transformation experiments. The results confirmed a measurable amount of transforming DNA to be present in these crude preparations, and that this DNA could be destroyed by treatment with DNase I (Table 2). Comparable results were obtained when strain P271 was incubated under planktonic conditions. Notably, a recent report has demonstrated that pneumococcal EV harbor a nucleotide sequence-independent endonuclease (TatD) capable of degrading neutrophil extracellular traps [33]. In this context, the amount of transforming DNA found in our experiments may represent only a portion of the total EV-associated eDNA.

## Discussion

Biofilm ECM contains eDNA, but its active role in biofilm appearance and maintenance was not recognized until Whitchurch et al. added DNase I to a *Pseudomonas aeruginosa* biofilm and watched the biofilm disappear [34]. Since then, many reports have confirmed that bacteria require eDNA to establish and maintain biofilms. The destruction of this eDNA provides a way of fighting biofilm-producing pathogens. Indeed, clinical studies have shown that aerosolized DNase I (dornase alpha, a recombinant DNase I from the human pancreas) is highly effective in this respect, improving the lung function of patients with cystic fibrosis [35].

In vivo studies have shown that eDNA is a major element of biofilms. However, whether it is of bacterial or environmental (including host) origin (or both) is controversial; certainly it is difficult to determine which is the case under in vivo conditions. Studies using *in vitro*

biofilm models provide a convenient way to screen large sets of strains, treatments, or growing conditions [36].

Among the possible origins of eDNA in pneumococcal biofilms, autolysins (either from bacterial or phage origin) have been proposed to have critical role. Previous studies have employed indirect (e.g., DNase I treatment and/or intrabiofilm transformation experiments) and direct methods (e.g., staining with a variety of DNA-specific fluorophores) to disclose the presence of eDNA in pneumococcal biofilms [7–9]. Immunostaining with α-dsDNA combined with CLSM also revealed the existence of long filaments of eDNA in biofilms ECM [37,38]. Moreover, the presence of eDNA-containing fibrous structures in the ECM of *Staphylococcus aureus* and *Propionibacterium acnes* biofilms has also been reported using α-dsDNA and atmospheric scanning electron microscopy [39,40]. The use of different technical approaches reinforces the idea that the fibrous assemblies of eDNA observed in some bacterial biofilms actually exist and also offers a novel perspective of the ECM structure of pneumococcal biofilms. Since most of the DNA filaments were found at the top of the mature biofilm (where actively growing cells reside) within 3 h of growth (Figure 1), it is unlikely that these eDNA fibers were formed exclusively via autolysis. The same conclusion might be drawn from the CLSM images of immunostained planktonic cultures (Figure 2).

In agreement with previous results, pneumococcal mutants either lacking the major autolysins or deficient in Com or LuxS/AI2 QSs showed limited biofilm-forming capacity. However, the results obtained following DNase I treatment of growing or pre-formed biofilms strongly suggest that those biofilms still contain eDNA. Direct CLSM visualization of the corresponding immunostained biofilms fully confirmed the presence of eDNA, even when the pneumococci were incubated in the presence of 2% choline chloride; this is known to induce the complete non-competitive inhibition of CBPs with enzyme activity, and to release all CBPs, whether enzymatic or not, from their bacterial surface attachments. It should be noted, however, that even at this high concentration, choline does not separate the CBP–DNA complexes that form part of the ECM of S. pneumoniae biofilms [9,10]. Nevertheless, since the complete inhibition of the enzymatic activity of autolysins takes place under these conditions, an exclusive, direct role for such enzymes in eDNA release appears to be unlikely. More direct evidence was obtained using biofilms formed by strain P204, a triple Δ*lytA* Δ*lytC* Δ*cbpD* mutant, in which the presence of eDNA was also verified (Figure 4). The release of eDNA was also observed in biofilms formed by Δ*comA* mutants or combined Δ*comA*/autolysin-deficient mutations. Most notably, the existence of biologically active eDNA in pneumococcal biofilm, even when autolysin-deficient strains were used —was fully confirmed by in situ reciprocal transformation experiments (Table 1). Deletion of either *lytA*, *lytC* and/or *cbpD* does not alter the transformability of the mutants compared to their parental strains when chromosomal DNA or plasmid(s) is used as donor material. Wei and Håvarstein studied the impact of LytA, LytC and CbpD on transformation efficiency in biofilm-grown pneumococci using an approach with some similarity to that employed here [21]. The authors made use of *in vitro* mixed biofilms containing Spc-resistant ($Spc^r$) Δ*comA* 'attacker cells' — harboring concomitant deletions in the three autolysin genes (strain SPH149), or not (strain RH1) — and $Nov^r$ non-competent (Δ*comA* Δ*comE*) 'target cells' (strain RH401). Upon the addition of CSP, the attackers (but not the targets, due to their being Δ*comE*) acquired competence and were transformed by the DNA released from the target cells through the fratricidal killing caused by the lytic enzymes induced by the attackers. A ca. 40-fold reduction in transformation efficiency was observed in biofilms composed of SPH149 attackers (autolysin-deficient) and RH401 cells (0.009%) with respect to that seen in biofilms containing the same target cells but involving a lysis-proficient strain (RH1) as the attacker (0.34%). Moreover, a further near 40-fold reduction in gene transfer frequency (0.00026%) was seen when SPH149 attackers were incubated with Δ*lytA* Δ*lytC* targets cells (strain SPH148) [21]. Target cells containing a Δ*cbpD* mutation were not tested, possibly because, as previously reported for mixed planktonic cultures, CbpD-proficient attacker cells (RH1) were 1000-fold more efficient in transformations involving $cbpD^+$ target cells than when CbpD-deficient attacker cells were used [41].

Pneumococcal biofilms that form during nasopharyngeal colonization may provide an optimal environment for increased genetic exchange with enhanced natural transformation in vivo. The presence of eDNA in the biofilm matrix has generally been attributed to the autolysis of a subpopulation of cells via fratricidal killing, suicidal killing, and/or the controlled release of DNA via signal transduction [16]. Autolysis-independent eDNA release has been documented in some Gram-positive bacteria [42,43]. Taking the present results together, it is clear that mechanisms involved in active eDNA release (perhaps associated with the production of EV), other than those directly dependent on autolysins, are at work in S. pneumoniae. This is important since an important feature of biofilms is the development of chemical gradients (i.e., pH, redox potential, and ions) [26]. For example, in *P. aeruginosa* biofilms the pH value towards the center of a microcolony (≈ 6.0) is lower than that at the edge of the biofilm or in the growth medium (≈ 6.8) [44], partly due to the local accumulation of eDNA [45]. Although not directly tested, a similar situation might be relevant in pneumococcal biofilms because it is well known that S. pneumoniae autolysis is inhibited at low pH values (≤ 6.0). In this case, autolysin-independent DNA release would allow the maintenance of horizontal gene transfer events within the biofilm. Although the amount of biologically active DNA released in the absence of detectable autolytic activity is limited, it appears to be sufficient to partially promote a biofilm lifestyle and, importantly, to allow horizontal gene transfer. It is also possible that, as suggested by the CLSM observations, a substantial amount of eDNA may be present in biofilms, although lacking most transforming activity. It is tempting to speculate that the DNA–protein complexes present in the ECM may hinder the biological activity of eDNA as a transforming agent while contributing to the formation and preservation of the biofilm.

Release of EV is considered as an important part of the general stress response at least in Gram-negative bacteria [46]. In contrast, the generation and release of Gram-positive EV through the thick cell wall is still being disputed, although it is considered that EV play important roles in virulence and horizontal gene transfer, and can contribute to microbial survival or competition (reviewed in ref. 47]. As reported for *Streptococcus mutans*, lysis-independent EV can transport DNA, contributing to horizontal gene transfer [48]. Recent results also suggest that signal transduction mechanisms may be involved in the regulation of EV production in some Gram-positive bacteria [49], but evidence for this is lacking in S. pneumoniae. As strongly suggested by the inhibitory effect of DNase I treatment in transforming efficiency, the biologically active eDNA released independent of detectable autolysis in S. pneumoniae appears to be located outside the EV. Although the loading of DNA into EV is thought to be widespread, experimental evidence showing that most EV-associated genomic DNA is present externally has been recently shown in *P. aeruginosa* and, possibly, other Gram-negative bacteria [50, 51]. However, other possibilities are also conceivable. For example, the stability of EV under various conditions may vary as it has been shown that surfactin produced by *Bacillus subtilis*

disrupts EV, releasing their contents into the environment [24]. Besides, a vesicle that loses membrane integrity may 'leak' its constituents into the supernatant (vesicle destabilization), rather than break up. This appears to be the effect of albumin or serum on EV of *Bacillus anthracis*, S. aureus and other microorganisms [52,53]. Interestingly, two recent studies have reported that the LytA NAM-amidase is not needed for production of EV, although the presence of EV-associated DNA was not analyzed [33,54].

An alternative (or complementary) mechanism for eDNA release may be bacterial type IV secretion systems (T4SS) that selectively deliver macromolecules to other cells or to the extracellular medium. An outstanding feature of these secretion systems is their ability to secrete both proteins and DNA molecules, a particularity that distinguishes them from other types of secretion system. The existence of a type IV secretion-like system involved in eDNA secretion was first described in *Neisseria gonorrhoeae* [55]. More recently, it has been found that the release of eDNA from the cytoplasm of H. influenzae into the ECM requires the expression of an inner-membrane complex with homology to type IV secretion-like systems, plus the ComE outer-membrane pore through which the type IV pilus is extruded [56]. Type IV pili are surface-exposed fibers that mediate many functions in bacteria, including locomotion, adherence to eukaryotic cells, biofilm formation, DNA uptake (competence), and protein secretion. Although initially considered to be exclusive to Gram-negative bacteria, they are also present in Gram-positive, although their role(s) is just beginning to emerge. Recently, several studies have revealed the existence of type IV competence-induced pili — predominantly composed of the ComGC pilin — on the surface of S. pneumoniae cells [57]. Since these pili bind DNA, it has been proposed that the transformation pilus is the primary DNA receptor on the bacterial cell during transformation in S. pneumoniae. It is tempting to speculate that, during competence, intracellular DNA may also be secreted into the ECM with the participation of the type IV pili, perhaps involving the aqueous pore formed by ComEC in the cytoplasmic membrane. Further studies are required to test this hypothesis.

Our results show that biofilm formation by S. pneumoniae requires the presence of eDNA as a component of the ECM. Although the pneumococcal cell wall-degrading enzymes LytA, LytC, and CbpD are important for optimal biofilm formation *in vitro*, CLSM imaging and genetic transformation experiments have demonstrated that mutants lacking all these enzymes still produce substantial amounts of eDNA. In addition, our results suggest that S. pneumoniae EV may carry biologically active, surface-associated eDNA.

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