Antigen-43-mediated autoaggregation impairs motility in Escherichia coli

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Functional interaction between bacterial surface-displayed autoaggregation proteins such as antigen 43 (Ag43) of Escherichia coli and motility organelles such as flagella has not previously been described. Here, it has been demonstrated for the first time that Ag43-mediated aggregation can inhibit bacterial motility. Ag43 overexpression produces a dominant aggregation phenotype that overrides motility in the presence of low levels of flagella. In contrast, induction of an increased flagellation state prevents Ag43-mediated aggregation. This phenomenon was observed in naturally occurring subpopulations of E. coli as phase variants expressing and not expressing Ag43 revealed contrasting motility phenotypes. The effects were shown to be part of a general mechanism because other short adhesins capable of mediating autoaggregation (AIDA-I and TibA) also impaired motility. These novel insights into the function of bacterial autoaggregation proteins suggest that a balance between these two systems, i.e. autoaggregation and flagellation, influences motility.

INTRODUCTION

The ability of bacteria to colonize and cause infection is often linked to the expression of specific surface structures. Examples include fimbriae that mediate attachment, flagella that mediate motility, aggregation factors that mediate cell clumping, and a capsule, which provides protection against phagocytosis and host defences. Although the function of these surface structures is often antagonistic, very little is understood regarding the molecular interactions that contribute to their contrasting phenotypes.

Antigen 43 (Ag43) is an autotransporter (AT) protein of Escherichia coli that promotes bacterial cell-to-cell aggregation (Diderichsen, 1980; Hasman et al., 1999; Henderson & Owen, 1999; Owen, 1983). It can be expressed on the E. coli cell surface in very high numbers (up to 50,000 copies per cell), resulting in a characteristic frizzy colony morphology (Hasman et al., 2000; Henderson & Owen, 1999; Owen, 1992). Ag43-mediated aggregation is a distinct phenotype that can be visualized macroscopically as flocculation and settling of cells in static liquid suspensions. The protein belongs to the AIDA group of AT proteins and exhibits a high degree of homology to several other members of the AT protein family, namely the AIDA-I adhesin involved in diffuse adherence of enteropathogenic E. coli and the TibA adhesin of enterotoxigenic E. coli (Sherlock et al., 2004, 2005). Ag43 is cleaved into two subunits (α and β), each constituting roughly half of the protein. The β subunit is believed to be an outer-membrane pore-forming component through which Ag43α gains access to the bacterial surface. The α subunit, on the other hand, remains attached to the bacterial cell surface via interactions with the β subunit (Henderson et al., 2004). The expression of Ag43 is phase-variable with switching rates of ~10⁻³ per cell per generation due to the concerted actions of Dam methylase (positive regulation) and OxyR (negative regulation) (Henderson & Owen, 1999; Schembri & Klemm, 2001; Schembri et al., 2003a; Waldron et al., 2002).

Ag43 dramatically enhances biofilm formation (Danese et al., 2000; Kjaergaard et al., 2000b; Reisner et al., 2003) and is specifically correlated with the biofilm mode of growth (Schembri et al., 2003b). Recent work has demonstrated that Ag43 expression is correlated with biofilm formation by uropathogenic E. coli during infection of bladder cells (Anderson et al., 2003) and in enteropathogenic E. coli (Torres et al., 2002). Mutations that destroy the function of the gene encoding Ag43 (i.e. flu) affect biofilm formation (Reisner et al., 2003; Schembri et al., 2003b). Ag43-mediated clumping also protects bacteria against killing agents like hydrogen peroxide (Schembri et al., 2003a).

In contrast to autoaggregation, motility contributes to colonization of different environmental niches by facilitating the spread of the infecting agent (Josenhans & Suerbaum, 2002). Different modes of surface colonization have been described and are linked to the expression of organelles that allow organisms to swim, swarm and dart. Flagella and type IV pili are prominent organelles that contribute to motility...
Co-ordinated expression of these organelles is achieved by tightly regulated signalling systems that involve the various genes encoding them (up to 50 genes contribute to E. coli flagella biosynthesis), which are, in some cases, coupled to quorum sensing systems (Harshey, 2003; Soutourina & Bertin, 2003). Environmental conditions, including moisture, temperature and nutrient availability, affect motility, and unique peptides or polysaccharides are thought to signal transcriptional activation of motility organelles in some species (Harshey, 2003). The master regulator that controls expression of flagella in Enterobacteriaceae is flhDC (Eberl et al., 1996; Macnab, 1992; Soutourina & Bertin, 2003).

Autoaggregation mediated by Ag43 and motility appear to play distinct roles in bacterial colonization, survival and spread. However, although autoaggregation and motility are opposing phenotypes predicted to act in an antagonistic manner, functional interactions between aggregation factors and motility organelles have hitherto not been studied. Here, we investigated the dynamics that occur between Ag43 and flagella and demonstrate that autoaggregation driven by Ag43 (and other homologous AT proteins, including AIDA-I and TibA) impairs bacterial aggregation driven by Ag43 (and other homologous AT proteins, including AIDA-I and TibA) impairs bacterial motility. Naturally occurring phase variants of proteins, including AIDA-I and TibA) impair aggregation driven by Ag43 (and other homologous AT proteins, including AIDA-I and TibA) impair bacterial motility. Naturally occurring phase variants of proteins, including AIDA-I and TibA) impair aggregation driven by Ag43 (and other homologous AT proteins, including AIDA-I and TibA) impair bacterial motility. Naturally occurring phase variants of proteins, including AIDA-I and TibA) impair aggregation driven by Ag43 (and other homologous AT proteins, including AIDA-I and TibA) impair bacterial motility. Naturally occurring phase variants of proteins, including AIDA-I and TibA) impair aggregation driven by Ag43 (and other homologous AT proteins, including AIDA-I and TibA) impair bacterial motility.

**METHODS**

**Bacterial strains, plasmids and DNA manipulations.** E. coli K-12 reference strain MG1655 was used in this work. Additional strains and plasmids are listed in Table 1. Bacteria were grown from glycerol stocks overnight on Luria–Bertani (LB) agar and in LB broth at 37°C with shaking unless otherwise stated. Strains containing expression plasmids with an inducible promoter were grown in media supplemented with IPTG as indicated. Ampicillin (100 μg ml⁻¹), chloramphenicol (30 μg ml⁻¹) and kanamycin (50 μg ml⁻¹) were used to maintain plasmids. DNA purifications, PCR, cloning and transformations were performed according to methods described elsewhere (Sambrook & Russell, 2001). Plasmid purification columns were purchased from Qiagen (Australia) and restriction enzymes from New England Biolabs (Canada).

**Semi-solid agar assay for assessment of motility.** To evaluate motility in different strains, overnight cultures were prepared in LB broth and resuspended to an OD₆₀₀ of approximately 0–35 (BioSpec-mini; Shimadzu). One microlitre of suspension was spotted onto the centre of a fresh 0-25% LB agar plate (n=4), supplemented with the appropriate inducer and antibiotic, using a sterile graded inoculation loop. Plates were incubated at 37°C for 16–24 h and motility was determined by measuring the distance between the centre of the agar and the leading edge of bacterial growth. Data are shown as the mean diameter (mm) of movement ± SEM for at least three independent experiments.

**Transmission electron microscopy (TEM).** TEM was used to detect flagella on bacteria grown on semi-solid agar and in broth. A 10 μl bacterial cell suspension (OD₆₀₀ ~ 2-0) was adsorbed onto a glow-discharged Formvar-coated copper grid. After 1 min the grid was washed carefully in sterile distilled water and visualized on a JEOL JEM 1010 transmission electron microscope operated at 80 kV. In each experiment, control strains not carrying relevant plasmids, or grown under the appropriate non-induced (versus induced) conditions, were included for comparison.

**Suspension autoaggregation assay.** To assess autoaggregation in different strains, we used the suspension clumping assay to monitor bacterial settling over time (Hasman et al., 1999). Overnight LB cultures supplemented with the appropriate antibiotics and inducer were mixed well prior to the start of the assay. Fifty microlitre samples (n=4) were taken approximately 0.5 cm below the surface.

**Table 1. Strains and plasmids**

<table>
<thead>
<tr>
<th>Strain or plasmid</th>
<th>Relevant characteristic(s)</th>
<th>Reference</th>
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<tr>
<td><strong>E. coli strains</strong></td>
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<tr>
<td>BD1428</td>
<td>K-12 reference strain</td>
<td>Diderichsen (1980)</td>
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<td>MG1655</td>
<td>K-12 reference strain</td>
<td>Bachmann (1996)</td>
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<td>MS426</td>
<td>MG1655 ΔflhDC</td>
<td>Reisner et al. (2003)</td>
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<td>MS427</td>
<td>MG1655 Δflu</td>
<td>Reisner et al. (2003)</td>
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<td>MS641</td>
<td>MG1655 oxyR::kan</td>
<td>Schembri et al. (2003a)</td>
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<td>MS680</td>
<td>STEC O26; Ag43 phase-off</td>
<td>This study</td>
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<td>MS684</td>
<td>STEC O26; Ag43 phase-on</td>
<td>This study</td>
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<tr>
<td>MS1287</td>
<td>MG1655 ΔmotAB</td>
<td>This study</td>
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<td><strong>Plasmids</strong></td>
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<tr>
<td>pFHC2235</td>
<td>dam gene from MG1655 in pUC19</td>
<td>Schembri et al. (2004)</td>
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<tr>
<td>pKK128</td>
<td>flu gene from MG1655 in pACYC184</td>
<td>Kjaergaard et al. (2000a)</td>
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<tr>
<td>pMG600</td>
<td>flhDC operon from Serratia in pVL133</td>
<td>Givskov et al. (1995)</td>
</tr>
<tr>
<td>pRMV3</td>
<td>tibA gene from H10407 in pACYC184</td>
<td>Sherlock et al. (2005)</td>
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<td>pKD46</td>
<td>t-Ren recombinase expression plasmid</td>
<td>Datsenko &amp; Wanner (2000)</td>
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<tr>
<td>pCP20</td>
<td>FLP synthesis under thermal control</td>
<td>Cherepanov &amp; Wackernagel (1995)</td>
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of the liquid cultures at 15 min intervals, transferred to a round bottom microtitre plate (TPP; Europe) and OD_{600} was measured by a microtitre plate reader. Data are shown as the mean absorbance ± SD, where the degree of autoaggregation is inversely proportional to the turbidity.

Assessing Ag43-mediated autoaggregation as a function of flagella. To analyse whether a balance between Ag43-mediated autoaggregation and flagella expression might influence motility, we examined autoaggregation in the presence of increasing flagella expression. E. coli MG1655 was transformed with two plasmids: (i) pKKJ128 (constitutive Ag43 expression); and (ii) pMG600 (IPTG-inducible flagella expression) (Givskov et al., 1995). The effect of increased flagella expression on the clumping activity of Ag43 was assessed by growth in the presence of increasing concentrations of IPTG followed by the autoaggregation assay as above. Similar experiments were performed using overnight liquid cultures inoculated onto the surface of semi-solid agar containing different concentrations of IPTG to study whether a balance between these expression states influences motility. TEM was used to assess flagella expression under the different growth conditions and immunoblotting was used to assess both Ag43 and flagella (FIC) levels.

Immunoblotting. To prepare immunoblots, 100 µl of an overnight LB broth culture was boiled for 10 min and the protein concentration was determined by using the Bradford assay. Three micrograms of protein were mixed with SDS loading buffer, boiled for 10 min, cooled on ice and then separated on 12.5% Tris-SDS-PAGE gels run at 15 V cm⁻¹ for 60 min in Tris-SDS glycine running buffer, according to methods described in Sambrook & Russell (2001). Proteins were transferred to PVDF membranes (Biorad) by use of a mini trans-blot electrophoretic apparatus (Bio-Rad) run at 100 V for 60 min. Blots were blocked overnight in 5% skim milk in 0.1% PBS-Tween 20 (PBST) and probed with rabbit anti-Ag43 (1:5000) and anti-flagellin (1:1000) antibodies diluted in 5% skim milk in PBST with 0.1% sodium azide for 1 h at room temperature. Blots were washed three times in PBST and incubated with horseradish-peroxidase-conjugated anti-rabbit IgG (1:10000) for 1 h in 5% skim milk in PBST. Blots were washed three times in PBST and developed using 5-bromo-4-chloro-3-indolyl phosphate/nitro blue tetrazolium tablets (Sigma) dissolved in distilled water.

Construction of E. coli MG1655 ΔmotAB mutant. Electroporation competent cells of MG1655(pKD46) were prepared by growing the cells at 30 °C in ampicillin-SOB medium followed by washing of the cells extensively in ice-cold 10% glycerol in distilled water (Sambrook & Russell, 2001). Primers MOTABF (5'-TGCAAATGCGCTGTTCGCGCTTGGC-3') and MOTABR (5'-GTATATGGATCTGGCTTAAATGCGGACCATATGAATTATCCGC-3') were used to amplify a 1.6-kb PCR product from plasmid pKD4, representing the kanamycin resistance cassette from pKD4 and additional 50 bp overhang regions (underlined) in the 5' and 3' ends of the PCR product complementary to the motA and motB genes in E. coli MG1655. The PCR product was purified using a Qiagen PCR clean-up column and transformed into competent MG1655(pKD46). MG1655ΔmotAB transformants carrying the kanamycin cassette on the chromosome in place of motAB were selected on kanamycin plates at 37 °C and screened by PCR using k1 and k2 primers as described by Datsenko & Wanner (2000), as well as MOTSCF (5'-TCAATGTCACCAAGCTGGCTGCTC-3') and MOTSCR (5'-AGCTTGGAGCCTATCATTAACCC-3') in various combinations. The kanamycin cassette was removed from the chromosome of MG1655ΔmotAB::kan using plasmid pC20 as described by Datsenko & Wanner (2000). Plasmids pMG600 and pKKJ128 were then introduced into MG1655ΔmotAB by heat shock to give MG1655ΔmotAB(pMG600), MG1655ΔmotAB(pKKJ128) and MG1655ΔmotAB(pMG600, pKKJ128) which were maintained on kanamycin, chloramphenicol and both antibiotics, respectively.

Assessment of autoaggregation and motility in natural E. coli phase variants. Wild-type phase variants of E. coli BD1428 and MS680 were selected from LB agar plates based on morphological differences arising from differential expression of Ag43 (see Fig. 6). These colony variants (five of each) were inoculated into 5 ml LB broth, grown overnight at 37 °C, and 10 and 1 µl samples were used to inoculate 5 ml LB broth for the suspension autoaggregation assay, and semi-solid LB agar for the swimming motility assay, respectively. Data are shown as the mean values ± SEM (n = 5) for one independent experiment representative of several.

Statistics. Motility between different strains was compared using the non-parametric Kruskal–Wallis test (SPSS v9.0; SPSS Inc.). P values < 0.05 were considered significant. Aggregation was compared using Student’s t-test.

RESULTS

An E. coli oxyR mutant is non-motile

Several studies have shown that mutation or deletion of the E. coli stress response regulator gene oxyR results in over-expression of Ag43 (Haagmans & van der Woude, 2000; Hasman et al., 1999; Henderson & Own, 1999; Schembri & Klemm, 2001; Schembri et al., 2003a). As a result, E. coli oxyR mutants display a strong clumping phenotype. During further characterization of an E. coli K-12 oxyR mutant (MS641) (Schembri et al., 2003a), we observed that it displayed altered motility characteristics. This prompted us to perform a detailed comparison of the motility phenotype between MS641 and its wild-type (WT) parent strain MG1655. MS641 displayed an acute impairment in swimming ability (Fig. 1a–c) that correlated with increased Ag43-mediated clumping (Fig. 1d). This observation was not strain-dependent since several independently constructed E. coli K-12 oxyR mutants at our disposal also displayed this phenotype (data not shown). These data implied that the severely impaired motility of MS641 may be due to an abundance of the Ag43 autoaggregate at the bacterial surface. However, because OxyR is a global regulator that affects the activity of numerous bacterial expression pathways, further experiments were performed to extraneous OxyR affects.

Enhanced Ag43 expression through Dam methylation impairs motility

To circumvent interference from OxyR-regulated factors separate from Ag43, we employed the Dam-methylation plasmid pFCH2235. This plasmid contains the E. coli dam gene cloned directly downstream of the IPTG-inducible lacZ promoter. Overexpression of the Dam methylase after IPTG induction results in methylation at the GATC sites located within the flu gene promoter and this prevents repression by OxyR (Haagmans & van der Woude, 2000; Wallecha et al., 2002). In E. coli MG1655 transformed with pFCH2235, motility was completely ablated, in contrast to the rapid
motility of MG1655 (Fig. 2a). This effect was contingent upon the presence of IPTG, demonstrating the requirement for Dam methylation. This observation supported the notion that impaired motility in MS641 is due to overexpression of Ag43 rather than alternative OxyR-regulated effects. MG1655(pFHC2235) cells at the periphery of growth readily expressed flagella (TEM data not shown).

**Ag43-mediated inhibition of motility is independent of regulatory systems**

To confirm whether Ag43 directly and specifically acts as an inhibitor of motility, we used the Ag43 constitutive expression plasmid pKKJ128 (Kjaergaard et al., 2000a, b). pKKJ128 was transformed into the previously characterized MG1655Δflu strain MS427 (Reisner et al., 2003), which lacks the ability to express Ag43. When MS427(pKKJ128) was grown on 0–25% agar it was completely impaired in its ability to swim (Fig. 3), consistent with the notion that Ag43-mediated aggregation prevents motility. Furthermore, since the flu gene is constitutively transcribed by the tetracycline gene promoter in pKKJ128, Ag43-mediated inhibition of motility occurs completely independently of the regulatory mechanisms that control Ag43 expression (i.e. OxyR repression and Dam methylation). Taken together, these data demonstrate that, under these growth conditions, Ag43 overexpression causes a dominant aggregation phenotype that impedes motility.

**Ag43 homologues TibA and AIDA-I also impair motility**

The AIDA-I and TibA AT proteins display approximately 25% amino acid identity to Ag43, possess similar functional characteristics and promote cell-to-cell aggregation (Sherlock et al., 2004, 2005). To investigate whether these proteins also impair motility in a manner similar to Ag43, we analysed MG1655 transformants containing plasmids leading to the constitutive overexpression of TibA or AIDA-I. Overexpression of TibA and AIDA-I significantly

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**Fig. 1.** Ag43 over-expressing OxyR-deficient E. coli MG1655 displays impaired swimming motility compared to the wild-type parent strain. Comparisons between strains were made using a semi-solid agar motility assay. MG1655 is highly motile (a) compared to strain MS641 (b) which lacks functional oxyR and therefore produces abundant amounts of the autoaggregator Ag43. The abatement of motility in MS641 is shown in (c: ▲, MS641; ○, MG1655), which is predicted to result from the proficient clumping activity of Ag43 (d).

**Fig. 2.** Dam methylation in E. coli MG1655 enhances Ag43 expression and impedes motility. Transformation of plasmid pFCH2235 containing an IPTG-inducible dam methylase gene into E. coli MG1655 ablated motility in this strain as compared to the characteristic rapid swimming motility of MG1655. □, MG1655; ▲, MG1655(pFCH2235); △, MG1655

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impaired motility (Fig. 4), an observation consistent with our findings with Ag43.

Increased flagellation can counteract Ag43-mediated inhibition of motility

Based on these observations, we hypothesized that a balance exists between flagellation and autoaggregation and this might influence motility via the dominance of one phenotype over the other. We therefore investigated whether overexpression of flagella could counteract the ability of Ag43 to inhibit motility. A system of controlled flagella expression, as described by Givskov et al. (1995), was used in which the master regulator flhDC genes are cloned behind an IPTG-inducible promoter on the pVLT33 plasmid (pMG600). Using this system, we examined motility of E. coli MG1655 containing pMG600 in the presence of increasing amounts of IPTG (i.e. corresponding to increasing amounts of flagella), and E. coli MG1655 containing both pMG600 and pKKJ128 for constitutive expression of Ag43. Few flagella were detected in E. coli MG1655(pMG600) grown without supplemental IPTG as assessed by TEM, while increased flagellation was observed with increasing concentrations of IPTG (Fig. 5a). Semisolid agar motility assays demonstrated that impaired motility in MG1655(pKKJ128, pMG600) could be reversed when 10 μM IPTG was added to the medium to increase flagellation (Fig. 5b).

Increased flagellation also inhibits autoaggregation

Ag43 belongs to a class of short non-organelle-type adhesins and thus aggregation requires close cell–cell contact. To assess whether flagella expression interfered with Ag43-mediated cell–cell aggregation, we investigated if overexpression of flagella could counteract the ability of Ag43 to mediate cell clumping. MG1655(pMG600) transformants containing pKKJ128 clumped strongly compared to the control strain MG1655(pACYC184) (data not shown). In conditions of low flagella expression in MG1655(pKKJ128, pMG600), the clumping phenotype mediated by Ag43 could not be overcome (Fig. 5c). However, increased flagellation (100 μM IPTG) counteracted Ag43-mediated autoaggregation (Fig. 5c). The difference in aggregation was not related to the level of Ag43 expression, since immunoblot analysis demonstrated equivalent amounts of Ag43 protein in conditions of increased flagella synthesis (Fig. 5d). Flagella overexpression also counteracted the autoaggregation phenotype mediated by AIDA-I (plasmid pOS33) and TibA (plasmid pRMV3) (data not shown). Taken together,
these data demonstrate that under these growth conditions increased flagellation can counteract autoaggregation driven by surface structures such as Ag43.

The above data can be interpreted in two ways: (i) increased flagellation results in physical shielding of the intimate contact required for Ag43–Ag43 aggregation, or (ii) flagella-mediated motility prevents Ag43–Ag43 interactions as a result of dynamic bacterial cell movement. To test these hypotheses, we constructed a non-motile but flagellated mutant by insertional inactivation of the \textit{motAB} genes (MS1287). When MS1287 was transformed with plasmids pMG600 (\textit{flhDC}+) and pKKJ128 (\textit{flu}+) and grown under flagella-inducing conditions, it did not aggregate (data not shown), suggesting that physical interference via induction of hyper-flagellation is able to prevent Ag43-mediated aggregation. We note that this does not preclude the possibility that flagella-driven bacterial movement may also reduce the efficiency of Ag43-mediated aggregation.

\textbf{Ag43-mediated inhibition of motility occurs in natural phase-variant subpopulations of \textit{E. coli} K-12}

Ag43 expression is phase-variable and subpopulations of phase-on and phase-off cells can be identified by distinct differences in colony morphology. The \textit{E. coli} reference strain BD1428 (alias X474) undergoes colony morphology

\fig{5}{Increased flagellation can counteract Ag43-mediated inhibition of motility and autoaggregation. (a) TEMs of MG1655(pKKJ128, pMG600) grown in the presence of increasing concentrations of IPTG for increasing flagella expression. Bars, 2 μm. (b) Motility assay demonstrating that MG1655(pKKJ128) was completely non-motile in contrast to MG1655(pMG600) when grown in 10 μM IPTG and assessed at 16 h. Comparison with MG1655(pKKJ128, pMG600) demonstrates that increased flagellation can counteract the inhibition of motility in MG1655(pKKJ128) brought about by overexpression of Ag43. Representative plates corresponding to MG1655(pKKJ128), MG1655(pMG600) and MG1655(pMG600, pKKJ128) are shown on the right. (c) Settling assay demonstrating the effect of increased flagellation on autoaggregation mediated by Ag43 in MG1655(pKKJ128, pMG600). Low level flagella expression (0-01 μM IPTG, ○) did not affect autoaggregation, whereas increased flagellation (100 μM, ■) impaired Ag43-mediated clumping. (d) Immunoblot analysis demonstrating equivalent levels of expression of Ag43 in MG1655(pMG600, pKKJ128) regardless of the level of flagella expression, which is demonstrated to increase in the presence of increasing concentrations of IPTG.
phase variation switching that gives rise to several different morphotypes (Hasman et al., 2000). Two of these morphotypes are the direct result of Ag43 switching: (i) flat frizzy colonies caused by Ag43 overexpression (i.e. Ag43 phase-on cells), and (ii) flat irregular-shaped colonies with a smooth surface (i.e. Ag43 phase-off cells) (Fig. 6a). To investigate whether the described interactions between autoaggregation and motility occur in natural phase-variant subpopulations of E. coli, we examined the motility of selected BD1428 colonies representing the Ag43 phase-on and Ag43 phase-off morphotypes. The Ag43 phase-on and phase-off variants exhibited profound differences in their ability to autoaggregate and swim in the semi-solid agar-motility assay. On the one hand, Ag43 phase-off cells did not aggregate (Fig. 6b) and were highly motile in the semi-solid agar swimming assay (Fig. 6c). Ag43 phase-on cells, however, which overexpress Ag43 (Fig. 6a), clumped strongly (Fig. 6b) and were entirely non-motile (Fig. 6c).

**Ag43 phase variants of a wild-type E. coli O26 also exhibit differences in motility**

To demonstrate if the above results are relevant to wild-type E. coli, we selected out phase-on and phase-off Ag43-expressing colonies from a wild-type Shiga toxin-producing E. coli (STEC) O26 strain. Ag43 phase-off (MS680) and phase-on (MS684) cells were selected by differences in colony morphology and Ag43 expression was verified by Western blotting with Ag43-specific antiserum (data not shown). In agreement with the results for the K-12 strain BD1428, Ag43 phase-off cells were motile while Ag43 phase-on cells were non-motile (Fig. 6d). These results illustrate that natural phase variation in Ag43 expression directly affects bacterial motility and that this phenomenon occurs naturally in subpopulations of E. coli.

**DISCUSSION**

Bacteria express numerous surface structures that enable them to interact with and survive in changing environments, e.g. flagella to swim and adhesins for attachment to surfaces. These surface components have highly diverse structures, and it must be implicit that they physically interfere with each other in such a way that the activity of one surface structure may sometimes be obstructed by the presence of another. We have previously demonstrated, for example, that both fimbriae and capsule physically block the actions of the considerably shorter Ag43 adhesin in E. coli (Hasman et al., 1999; Schembri et al., 2004). Interference between...
bacterial surface structures is likely to have important consequences on the interplay between these organisms and their environment, including host–pathogen interactions. Here, we have systematically studied the interactions between these traits (i.e. autoaggregation and motility) and have demonstrated for the first time that bacterial autoaggregation, a phenomenon mediated by Ag43 and other homologous AT proteins, inhibits bacterial motility.

Many bacteria, including Bordetella pertussis (Menozzi et al., 1994), Mycobacterium tuberculosis (Menozzi et al., 1996), Staphylococcus aureus (McDevitt et al., 1994) and Streptococcus pyogenes (Frick et al., 2000), form aggregates. This confers an ability to resist various host defences, e.g. complement attack and phagocytosis (Berge et al., 1997; Ochiai et al., 1993), which supports the notion that bacterial autoaggregation is an important virulence mechanism. Formation of aggregates usually takes place through autoaggregation of cells. In some cases, the underlying molecular mechanism is known, and self-recognizing surface proteins are often responsible for autoaggregation. A well-studied example is autoaggregation of S. pyogenes, which occurs through the intercellular interactions between pairs of protein H (Frick et al., 2000). Several different systems are independently capable of conferring autoaggregation in E. coli. Apart from the well characterized Ag43, AIDA-I and TibA AT proteins, a recent analysis of E. coli K-12 revealed several additional cryptic AT-encoding genes whose products are able to mediate aggregation (Roux et al., 2005). Other mechanisms of cell aggregation have also been described. Curli, for example, are extracellular surface organelles formed by the precipitation of secreted soluble subunit proteins into thin fibres (Hammar et al., 1996). Autoaggregation involves intercellular fibre precipitation mediated by a nucleator protein. Bundle forming pili (BFP), on the other hand, are a type IV class of fimbriae produced by enteropathogenic E. coli that emanate from the cell surface and align along their longitudinal axes to form bundles of filaments (Bieber et al., 1998; Giron et al., 1991). These are long, flexible, rope-like structures composed almost exclusively of a single repeating structural subunit referred to as BfpA (Giron et al., 1991). Expression of BFP mediates two phenotypes thought to play a role in colonization: autoaggregation in liquid cultures and localized adherence on tissue culture cell monolayers (Bieber et al., 1998). In enteroaggregative E. coli, two fimbrial types designated aggregative adhesive fimbriae I and II (AAF/I and AAF/II) have been identified (Czeczulin et al., 1997; Nataro et al., 1992). These flexible 2–3 nm wide structures mediate prominent autoagglutination of bacterial cells to each other (Nataro et al., 1987; Nataro & Kaper, 1998). Variants of the FimH adhesin of type 1 fimbriae also promote cell aggregation (Schembri et al., 2001; Schembri & Klemm, 2001). Contrary to organelle-mediated aggregation systems, AT proteins are anchored directly to the outer cell membrane. Thus, aggregation mediated by AT proteins results in a more intimate cell–cell contact compared to systems where the intercellular interactions are based on polymeric structures that protrude further from the bacterial surface, i.e. fimbriae and curli.

Several lines of evidence from the current study strongly suggest that bacterial autoaggregation interferes with motility: (i) E. coli oxyR mutants are non-motile, (ii) overexpression of the Dam methylase in E. coli relieves OxyR-mediated repression of Ag43 and prevents motility, (iii) constitutive expression of Ag43 prevents motility, (iv) the Ag43 homologues AIDA-I and TibA interfere with motility, and (v) E. coli cells expressing Ag43 in a ‘phase-on’ or ‘phase-off’ state exhibit striking non-motile and motile phenotypes, respectively. Here, the link between autoaggregation and motility is shown as a function of Ag43 phase variation where E. coli subpopulations can convert from a motile to non-motile phenotype.

Ag43 is predicted to protrude approximately 10 nm from the E. coli cell surface. The protein is present in up to 50 000 copies in K-12 strains and current evidence suggests it is localized around the entire cell surface. Our results suggest a model whereby Ag43-mediated aggregation prevents motility when flagella are present in low numbers (associated with a swimming phenotype). Increased flagellation may create a physical barrier that prevents the intimate contact required for Ag43–Ag43 interaction. This interference is consistent with the inhibition of Ag43-mediated aggregation by other surface structures (Hasman et al., 1999; Schembri et al., 2004). Alternatively, cell movement mediated by expression of flagella could prevent the intimate contact necessary for intercellular adhesion to become established by efficient homotypic Ag43 interactions. We tested the later hypothesis by constructing a motAB mutant in E. coli K-12. The products of motA and motB are required for flagella rotation, but do not contribute to the synthesis or export of flagella subunit proteins; thus the strain produces flagella, but is non-motile. Our results indicate that the induction of non-motile flagella is able to counteract Ag43-mediated aggregation, although this does not preclude the possibility that flagella-driven bacterial movement may also reduce the efficiency of Ag43-mediated aggregation. One of the implications of these observations is that any mechanism capable of mediating efficient cell–cell aggregation may affect motility.

Ag43 is widespread in E. coli and is expressed in many pathogenic strains. A survey of enteropathogenic and urinary tract infectious strains showed that 77 and 60 %, respectively, of these were capable of Ag43 expression (Owen et al., 1996). Moreover, many strains posses duplex or multiple copies of the gene, as seems to be the case in enteropathogenic and enterohemorrhagic subtypes (Klemm et al., 2004; Roche et al., 2001; Torres & Kaper, 2002). Functionally, Ag43 (and other homologous proteins) promotes bacterial adhesion and biofilm formation, both of which are closely associated with bacterial virulence. Flagella, on the other hand, are motility organelles that enable bacteria to move to different locations (e.g. for nutrient acquisition). Together, these two surface components play a significant role in biofilm
formation with most models predicting that they are expressed at different phases; flagella for motility as well as possibly initial adhesion, and Ag43 for aggregation and the development of microcolonies. Phase variation of Ag43 may represent one mechanism by which bacteria switch between the expression of these two important phenotypes to exploit their full repertoire of survival and virulence capabilities.

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REFERENCES


