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Published in:
I S M E Journal

DOI:
10.1038/ismej.2015.220

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Evolution of metabolic divergence in *Pseudomonas aeruginosa* during long-term infection facilitates a proto-cooperative interspecies interaction

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The effect of polymicrobial interactions on pathogen physiology and how it can act either to limit pathogen colonization or to potentiate pathogen expansion and virulence are not well understood. *Pseudomonas aeruginosa* and *Staphylococcus aureus* are opportunistic pathogens commonly found together in polymicrobial human infections. However, we have previously shown that the interactions between these two bacterial species are strain dependent. Whereas *P. aeruginosa* PAO1, a commonly used laboratory strain, effectively suppressed *S. aureus* growth, we observed a commensal-like interaction between the human host-adapted strain, DK2-P2M24-2003, and *S. aureus*. In this study, characterization by matrix-assisted laser desorption ionization-time of flight (MALDI-TOF) imaging mass spectrometry (IMS) and mass spectral (MS) molecular networking revealed a significant metabolic divergence between *P. aeruginosa* PAO1 and DK2-P2M24-2003, which comprised several virulence factors and signaling 4-hydroxy-2-alkylquinoline (HAQ) molecules. Strikingly, a further modulation of the HAQ profile was observed in DK2-P2M24-2003 during interaction with *S. aureus*, resulting in an area with thickened colony morphology at the *P. aeruginosa–S. aureus* interface. In addition, we found an HAQ-mediated protection of *S. aureus* by DK2-P2M24-2003 from the killing effect of tobramycin. Our findings suggest a model where the metabolic divergence manifested in human host-adapted *P. aeruginosa* is further modulated during interaction with *S. aureus* and facilitate a proto-cooperative *P. aeruginosa–S. aureus* relationship.

*The ISME Journal* (2016) 10, 1323–1336; doi:10.1038/ismej.2015.220; published online 18 December 2015

Introduction

Although many bacterial infectious diseases are assumed to be monoclonal, infections most often occur in a polymicrobial context within the host (Short et al., 2014). How the different microbes contribute to disease and health remains poorly understood, but it is becoming increasingly clear that interactions between bacterial pathogens and other microbial species residing in the infected host (such as co-infecting pathogens or commensal bacteria) may in some cases determine disease phenotype or the response to therapy (Peters et al., 2012; Short et al., 2014). It continues to be a central challenge to identify and characterize these interactions and the biological processes they control in relation to infection. Studies of microbe–microbe interactions and their impact on the activity of bacterial pathogens have often focused on well-characterized laboratory or reference strains (Moree et al., 2012; Korgaonkar et al., 2013; Vega et al., 2013). However, given the genetic diversity that often exists in pathogen populations and the clonal diversity that may evolve within the host during long-term infection (Lieberman et al., 2011; Marvig et al., 2013; Marvig et al., 2013), a major issue is how well the use of any one strain as an experimental model for understanding how microbial interactions modulate pathogen activity reflects this diversity.

To begin to address this issue, we investigate chronic airway infections in patients with cystic fibrosis (CF). Complex microbial communities reside in the CF airways, where the community structure and composition may vary between patients and can...
change dramatically over time depending on disease progression and antibiotic exposure (Zhao et al., 2012). Despite profound inter-individual microbial community dynamics, strains of the opportunistic human pathogens, *P. aeruginosa* and *S. aureus*, are among the dominant inhabitants in the CF airways and have been co-isolated in both early-stage as well as chronic late-stage infections (Lording et al., 2006; Harrison, 2007; Fugere et al., 2014). In accordance, a recent cohort study at the Danish CF Centre reported that approximately 16% of the CF patients chronically infected with *S. aureus* were also chronically infected with *P. aeruginosa* (Dalboge et al., 2013). Interaction studies between these two bacterial species often use laboratory model strains of *P. aeruginosa*, which effectively kills co-cultured *S. aureus* by producing a range of anti-staphylococcal molecules such as pyocyanin, LasA, LasB, rhamnolipids and the 4-hydroxy-2-alkylquinoline (HAQ) molecule, 4-hydroxy-2-heptylquinoline-N-oxide (HQNO) (Mashburn et al., 2005; Palmer et al., 2005; Hoffman et al., 2006; Mitchell et al., 2010; Korgaonkar and Whiteley, 2011; Korgaonkar et al., 2013; DeLeon et al., 2014). Therefore, limited investigations have addressed the potential effect of *S. aureus* on *P. aeruginosa.*

Important for *P. aeruginosa* pathogenesis is the hierarchical QS system, which is mediated by two chemically distinct classes of signaling molecules, the N-acylhomoserine lactones and the HAQ molecules (Pearson et al., 1997; Heeb et al., 2011). More than 50 HAQ molecules divided into five distinct series (the series A–E congeners) have been identified from *P. aeruginosa,* where especially the signaling molecule 3,4-dihydroxy-2-heptylquinoline (PQS; the most prominent Series B congener) is important for regulating the production of virulence factors (Deziel et al., 2004; Heeb et al., 2011). However, within bacterial populations associated with long-term infections, loci encoding the QS system have been found to accumulate mutations, and can result in extensive metabolic and phenotypic modifications of host-adapted strains compared with strains of environmental origin (Smith et al., 2006; D’Argenio et al., 2007; Yang et al., 2011; Damkiaer et al., 2013), which may subsequently affect their interaction with other microorganisms. Thus, the outcome of interaction between *P. aeruginosa* and *S. aureus* may be strain dependent.

This work expands on our previous observation with a human host-adapted *P. aeruginosa* strain, DK2-P2M24-2003, from a dominant lineage, DK2, that have evolved through decades of growth in chronically infected Danish CF patients (Yang et al., 2011; Damkiaer et al., 2013; Marvig et al., 2013). *P. aeruginosa* DK2-P2M24-2003 showed a distinct colony morphology with centered autolysis and a metallic sheen coverage associated with the area of autolysis (Figure 1) (Michelsen et al., 2014). Notably, in contrast to *P. aeruginosa* PAO1, which is a widely used laboratory strain in microbial interaction studies (Hoffman et al., 2006; Mitchell et al., 2010; DeLeon et al., 2014; Phelan et al., 2014), *P. aeruginosa* DK2-P2M24-2003 did not suppress the growth of *S. aureus* USA300 strain JE2. Instead a thickened colony morphology appeared at the interface with *S. aureus* JE2 (Figure 1). GFP expression measured from *P. aeruginosa* DK2-P2M24-2003 tagged with a growth rate-dependent promoter:reporter gene construct, demonstrated an increased *P. aeruginosa* cell density at the area of thickened colony (Michelsen et al., 2014). These results suggested a commensal-like interaction, where *P. aeruginosa* DK2-P2M24-2003 benefits from the interaction with *S. aureus.*

The goal of this study was to provide insight into the metabolic divergence between *P. aeruginosa* DK2-P2M24-2003 and PAO1, which facilitates the commensal-like interaction between *P. aeruginosa* DK2-P2M24-2003 and *S. aureus* JE2. By combining molecular genetics with matrix-assisted laser desorption ionization-time of flight (MALDI-TOF) imaging mass spectrometry (IMS) on agar surfaces and mass spectral (MS) molecular network analysis on microbial extracts, a significant divergence in production of antimicrobial and HAQ molecules was detected between PAO1 and DK2-P2M24-2003. Such metabolic divergence may explain the different interaction patterns with *S. aureus* observed by
PAO1 and DK2-P2M24-2003, respectively. Interestingly, the presence of *S. aureus* resulted in induction of a distinct HAQ profile in *P. aeruginosa* DK2-P2M24-2003 during interaction, which significantly differed from the otherwise autolysing HAQ profile detected in the DK2-P2M24-2003 monoculture and in interaction with the *S. aureus* agrC mutant. Furthermore, a *P. aeruginosa* HAQ-mediated protection of *S. aureus* from the antibiotic effect of tobramycin was observed. We therefore propose a model, where the HAQ molecules produced by *P. aeruginosa* DK2-P2M24-2003 provide an important factor for the proto-cooperative interaction with *S. aureus* JE2, in which both bacterial species benefit from the relationship.

**Materials and methods**

**Bacterial strains, plasmids and media**

The bacterial strains and plasmids used in this study are described in Table 1. *P. aeruginosa* and *S. aureus* were routinely cultured in LB broth/agar. *P. aeruginosa*–*S. aureus* interaction assays were performed on tryptic soy broth (Sigma-Aldrich, Denmark A/S) or artificial sputum medium (ASM) (Kirchner et al., 2012) supplemented with 1.2% (wt/vol) agar (Sigma-Aldrich, Denmark A/S) or artificial sputum medium (ASM) (Kirchner et al., 2012) supplemented with 1.2% agar. All liquid cultures were incubated at 37 °C with shaking (200 r.p.m.) unless otherwise stated. Antibiotics were used in following concentrations: ampicillin, 100 μg ml⁻¹; gentamicin, 60 μg ml⁻¹ for *P. aeruginosa* transposon and allelic replacement mutants; tetracycline, 50 μg ml⁻¹ for *P. aeruginosa* with inserted lux reporter fusion.

*P. aeruginosa–S. aureus* interaction assays. Stationary-phase cultures of *S. aureus* (optical density at 600 nm (OD600) of ~2) and *P. aeruginosa* (OD600 ~1.5) cultured in LB were diluted to OD600 ~0.2 and streaked or added as spots onto dry agar plates as previously described (Michelsen et al., 2014). Briefly, in the cross-streak assay, one loopful of *P. aeruginosa* culture was first streaked in one direction on the plate and left to dry before the plate was cross-streaked with one loopful of the *S. aureus* culture. During spot inoculation, 5 μl of the *P. aeruginosa* culture was spotted first onto agar plates and after drying 5 μl of the *S. aureus* culture was spotted with 5 mm distance from the *P. aeruginosa* spot. The experiments were carried out in triplicate, and the plates were incubated at 37 °C under aerobic conditions or anaerobically in a Type B Vinyl Anaerobic Chamber (Coy Lab Products, Grass Lake, MI, USA) filled with an atmosphere of 95% (vol/vol) nitrogen and 5% (vol/vol) hydrogen. After 24–72 h of incubation, the bacterial colonies touched the edge of each other with <1 mm distance between them. The plates were inspected visually, and the interaction at the *P. aeruginosa–S. aureus* interface was recorded.

The interaction assay with tobramycin was carried out as described by Hoffman et al. (2006). Briefly, the diluted *S. aureus* culture was applied to the surface of LB agar without or with addition of tobramycin (that is, 

**Table 1** Strains and plasmids used in this study

<table>
<thead>
<tr>
<th>Strain or plasmid</th>
<th>Genotype</th>
<th>Reference</th>
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<tr>
<td><strong>Plasmids</strong></td>
<td></td>
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<tr>
<td>pBT2</td>
<td>Gm&lt;sup&gt;+&lt;/sup&gt;; Himar1 C9 transposon</td>
<td>Kulasekara et al. (2005)</td>
</tr>
<tr>
<td>prK600</td>
<td>Cm&lt;sup&gt;+&lt;/sup&gt;; ori ColE1 RK2-mob&lt;sup&gt;+&lt;/sup&gt; RK2-mob&lt;sup&gt;+&lt;/sup&gt; helper plasmid for conjugation</td>
<td>Kessler et al. (1992)</td>
</tr>
<tr>
<td>pEXG2-PAO601</td>
<td>Gm&lt;sup&gt;+&lt;/sup&gt;; sacB, allelic exchange vector with PAO601 gene deletion fragment</td>
<td>This study</td>
</tr>
<tr>
<td>pCTX::pqsA&lt;sup&gt;+&lt;/sup&gt;-lux</td>
<td>Tet&lt;sup&gt;+&lt;/sup&gt;; Promoter region and part of pqsA fused to luxCDABE inserted into the miniCTX-1 delivery plasmid</td>
<td>Fletcher et al. (2007)</td>
</tr>
<tr>
<td>pHK-pqsH&lt;sup&gt;+&lt;/sup&gt;-lux</td>
<td>Tet&lt;sup&gt;+&lt;/sup&gt;; Promoter region and part of pqsH fused to luxCDABE inserted into the miniCTX-1 delivery plasmid</td>
<td>This study</td>
</tr>
<tr>
<td><strong>E. coli</strong></td>
<td>recA thi pro leu hisdRM&lt;sup&gt;+&lt;/sup&gt;; Sm&lt;sup&gt;+&lt;/sup&gt;</td>
<td>Kessler et al. (1992)</td>
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<td>HB101</td>
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<td><strong>P. aeruginosa</strong></td>
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<td>PAO1</td>
<td>WT, laboratory model strain</td>
<td>Stover et al. (2000)</td>
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<tr>
<td>PAO1_pqsH&lt;sup&gt;+&lt;/sup&gt;-lux</td>
<td>PAO1 containing a copy of the pqsH promoter linked to the luxCDABE genes in the chromosome</td>
<td>This study</td>
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<tr>
<td>DK2-P2M24-2003</td>
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<tr>
<td>DK2_pqsA&lt;sup&gt;+&lt;/sup&gt;-lux</td>
<td>DK2-P2M24-2003 containing a copy of the pqsA promoter linked to the luxCDABE genes in the chromosome</td>
<td>Michelsen et al. (2014)</td>
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<tr>
<td>DK2_pqsH&lt;sup&gt;+&lt;/sup&gt;-lux</td>
<td>DK2-P2M24-2003 containing a copy of the pqsH promoter linked to the luxCDABE genes in the chromosome</td>
<td>This study</td>
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<tr>
<td>DK2-Tn1</td>
<td>Transposon deletion of pqsB in DK2-P2M24-2003</td>
<td>This study</td>
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<tr>
<td><strong>S. aureus</strong></td>
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<td>JE2</td>
<td>Plasmid-cured derivative of USA300 (FPR3757)</td>
<td>Fey et al. (2013)</td>
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<tr>
<td>agrC</td>
<td>JE2 containing a transposon deletion of agrC</td>
<td>Fey et al. (2013)</td>
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0.5, 1.0, 1.25, 1.5, 1.75, 2.0 or 2.5 μg ml⁻¹) using a drigalski spatula, and 5 μl of the diluted P. aeruginosa cultures were added as spots to the S. aureus lawn. The experiments were carried out in triplicate, and the plates were incubated for 24 h at 37 °C.

Construction of reporter fusions and bioluminescence measurements

The plasmid pCTX::pqsA'-lux (Fletcher et al., 2007) was used for the pqsA transcriptional fusion experiment. For the pqsH::lux reporter fusion, a 389-bp fragment containing the intergenic region upstream of pqsH was amplified from genomic DNA using Phusion polymerase (Thermo Scientific) with the primers PqsH_F-PstI (5'−GAGACTGAGATCGCTGCACCGTGTCGTCGCGCAGTA-3') and pqsH_R-XhoI (5'−ACATCTCGAGTGTTGAATGAGCGCGCAACA-3') and ligated with T4 DNA ligase into pHK-CTX2-lux (Marvig et al., 2014) after double digestion of the PCR fragment and vector with the restriction enzymes XhoI and PstI. The resulting plasmid pHK-pqsH::lux or pCTX::pqsA'-lux was introduced into P. aeruginosa strain PAO1 or DK2-P2M24-2003, respectively by triparental mating (Trieuço et al., 1993) using the helper strain E. coli HB101/pRK600.

Diluted stationary phase cultures of P. aeruginosa PAO1 or DK2-P2M24-2003 containing the pqsH::lux or pqsA'-lux reporter fusions were spot-inoculated together with diluted stationary phase cultures of S. aureus on agar plates as described above. After 24 h of incubation, luminescence was recorded continuously for 10 s with a photon camera using Hamamatsu Argus 50 image processor (Unit One Laboratories, Berlin, Germany), and compared with the Genbank manufacturer, sequenced at LGC Genomics GmbH & Co, Düren, Germany), as described by the

Screen of S. aureus or P. aeruginosa transposon mutant libraries

The full S. aureus Nebraska transposon mutant library derived from S. aureus JE2 (Fey et al., 2013) was screened in a spot-inoculation setup with P. aeruginosa DK2-P2M24-2003 as illustrated in Supplementary Figure S5, to detect mutant strains which no longer induced the increased growth activity phenotype in P. aeruginosa. The S. aureus mutant strains were cultured in 200 μl LB in 96-well microtiter plates (Nunc) and P. aeruginosa DK2-P2M24-2003 in 50 ml LB over night (O/N) at 37 °C with shaking. Cultures of the S. aureus mutant strains were applied at one time onto OmniTrays (Nunc) containing LB agar by using a sterile replicator. After drying, the P. aeruginosa culture was applied in spots next to the S. aureus colonies using a sterile replicator. After 24–72 h of incubation the plates were visually inspected and S. aureus mutant strains were selected for a second round of screening using cross-streak and spot-inoculated assay as described above. The screening and rescreening were repeated three times.

Transposon mutagenesis of P. aeruginosa DK2-P2M24-2003 was performed with the himar1 C9 mariner transposon from pBT20 (Kulasekara et al., 2005) by triparental mating with the helper strain E. coli HB101/pRK600. Strain DK2-P2M24-2003 transconjugants with transposons integrated into the chromosome were selected on Pseudomonas isolation agar plates supplemented with gentamicin. Approximately 1500 mutants were screened for an impaired interaction with S. aureus JE2. The P. aeruginosa mutant strains were cultured in 200 μl LB in 96-well microtiter plates (Nunc) and S. aureus JE2 in 50 ml LB O/N at 37 °C with shaking and screened in a spot-inoculation setup as described above for the S. aureus mutant library as illustrated in Supplementary Figure S4. For mapping transposon insertion junctions in the P. aeruginosa DK2-P2M24-2003 chromosome, we used arbitrary PCR (Gaetano-Anolles, 1993). The PCR was performed in two rounds with two different sets of primers as described in Supplementary Table S1. The PCR products were purified using the NucleoSpin PCR clean-up kit (Macherey-Nagel GmbH & Co, Düren, Germany), as described by the manufacturer, sequenced at LGC Genomics GmbH (Berlin, Germany), and compared with the Genbank DNA sequence database using blastn (Altschul et al., 1990) and the P. aeruginosa DK2 reference genome (Accession no.: CP003149).

Construction of PAO601 deletion by allelic exchange in P. aeruginosa DK2-P2M24-2003

The PAO601 deletion in P. aeruginosa DK2-P2M24-2003 was performed using complete allelic exchange with a pEXG2-based construct containing a PAO601 gene deletion fragment, pEXG2-PAO601, kindly provided by M. Whiteley (University of Texas at Austin, USA). The allelic replacement construct was transferred into P. aeruginosa DK2-P2M24-2003 by triparental mating using the helper strain E. coli HB101/pRK600. After incubation O/N, merodiploid P. aeruginosa was selected by plating the conjugation mixture on Pseudomonas isolation agar plates with gentamicin (Gm) followed by incubation until colonies appeared. Colonies were restreaked on 6% sucrose/low salt (0.5% NaCl) LB agar plates. Sucrose-resistant/Gm-sensitive colonies were restreaked on 6% sucrose-low salt LB agar plates, screened for the presence of the mutated allele by PCR and verified by sequencing at LGC Genomics.

MALDI-TOF imaging mass spectrometry

P. aeruginosa was co-cultured with S. aureus using spot inoculation on thin TSA plates as described...
above (that is, 10 ml of medium in a standard Petri dish resulting in a medium thickness of about 1.5 mm). After 24–72 h of incubation, areas of agar media containing the microbial colonies were excised from the Petri dish and transferred onto the MALDI stainless steel target plate. The subsequent matrix application was performed using a 53-μm test sieve whereby dry matrix was deposited evenly across the sample surface until the desired matrix thickness was achieved. The sample was dried O/N followed by MALDI-TOF IMS analysis using a Bruker Microflex mass spectrometer. Data were collected from 50 to 3000 m/z at 80 Hz laser frequency at a spatial resolution of 400 μm × 400 μm using a Random Walk shot pattern. Data were analyzed using the Compass 1.2 software suite (FlexImaging 2.0, FlexControl 3.0 and FlexAnalysis 3.0; Bruker Daltonics, Bellerica, MA, USA) as previously described (Gonzalez et al., 2011). The resulting mass spectrum was binned at 0.5 m/z increments and manually inspected for masses of interest. Correlating the spatial distribution of signals between the bacterial monocultures and the bacterial interactions allowed identification of signal intensities of masses ascribed to a specific bacterial source. Each mass was visualized by a specific false color superimposed onto an optical image of the original sample plate. The MALDI-TOF IMS analysis was carried out in triplicate and only masses that were observed in all sample replicates were investigated further.

Results

Pseudomonas aeruginosa DK2-P2M24-2003 show divergent metabolic and interspecies interaction profiles

The interactions between P. aeruginosa strains PAO1 or DK2-P2M24-2003 and S. aureus JE2 were studied by culturing the bacteria side-by-side on agar surfaces in high-cell-density spots, which previously have been used to study microbial interactions (Gonzalez et al., 2011; Antonic et al., 2013; Michelsen et al., 2014; Phelan et al., 2014). Distinct colony morphologies and interaction patterns were observed by P. aeruginosa strains PAO1 and DK2-P2M24-2003, respectively, during co-culturing with S. aureus JE2 (Figure 2), which supported our previous observations (Michelsen et al., 2014). Whereas P. aeruginosa PAO1 developed a smooth, green-pigmented colony and inhibited the growth of S. aureus, DK2-P2M24-2003 instead showed a commensal-like interspecies interaction with a thickened colony morphology at the P. aeruginosa–S. aureus interface (Figure 2a), which previously has been identified as an area of increased Pseudomonas cell density (Michelsen et al., 2014). Importantly, the distinct interaction patterns by P. aeruginosa DK2-P2M24-2003 and P. aeruginosa PAO1, respectively, were reproducible during culturing on the different agar media, LB, TSA and ASM, which mimics the nutrient conditions of natural CF sputum, as well as both under aerobic and anaerobic growth conditions (Figure 3a).

The spatial and temporal distribution of metabolites was analyzed in the side-by-side P. aeruginosa–S. aureus interactions on agar surfaces by MALDI-TOF IMS (Yang et al., 2009). Differences in distribution of m/z signals between P. aeruginosa PAO1 and DK2-P2M24-2003 were examined and revealed very divergent metabolic profiles (Figure 2b). Several m/z signals were detected from P. aeruginosa PAO1, which were not present in P. aeruginosa DK2-P2M24-2003. These m/z signals corresponded to the antimicrobials pyocyanin (m/z 211, 1) and different rhamnolipids (for example, represented by m/z 673, 2) (Figure 2b) that previously have been identified from P. aeruginosa PAO1 using MALDI-TOF IMS (Phelan et al., 2014). In addition, some unidentified S. aureus m/z signals of m/z 231 (3) and m/z 256 (4) were observed with increased intensity at the interface with P. aeruginosa DK2-P2M24-2003 but not with P. aeruginosa PAO1 (Figure 2b), which could be due to the suppression of S. aureus by PAO1. Notable, the signaling HAQ molecule, HQNO, and the antimicrobial HAQ molecule, HQNO, (m/z 260, 6), both of which were present in P. aeruginosa PAO1, were not detected in P. aeruginosa DK2-P2M24-2003 (Figure 2b).
DK2-P2M24-2003 instead showed an increased production of 2-heptyl-4-hydroxyquinoline, HHQ (m/z 244, 5) (Figure 2b), the biosynthetic precursor of PQS (Deziel et al., 2004). PqsH catalyzes the conversion of HHQ to PQS in P. aeruginosa (Deziel et al., 2004). Thus, to investigate whether the lack of PQS production in P. aeruginosa DK2-P2M24-2003 was due to an altered expression of the pqsH gene, we constructed a luxCDABE-based pqsH promoter fusion (Becher and Schweizer, 2000), which was incorporated into the PAO1 and DK2-P2M24-2003 chromosome, respectively. Indeed, a significant decrease in pqsH expression, determined by emitted bioluminescence, was observed by P. aeruginosa DK2-P2M24-2003 compared with P. aeruginosa PAO1 (Figure 2c). Thus, given what is known about PQS and virulence factor production in P. aeruginosa (Deziel et al., 2004; Heeb et al., 2011), its loss could predict to facilitate co-existence of P. aeruginosa and S. aureus.

The presence of S. aureus JE2 induces a distinct HAQ profile and altered colony morphology in P. aeruginosa DK2-P2M24-2003. Compared with the metabolic profile of P. aeruginosa DK2-P2M24-2003 spotted in monoculture, we noticed by MALDI-TOF IMS an increased intensity...
of at least five *Pseudomonas*-derived molecules with the signals \( m/z \) 244, 258, 270, 272 and 298, respectively, at the *P. aeruginosa* DK2-P2M24-2003–*S. aureus* JE2 interface (Figure 4a). The increased intensity of the different molecules was most pronounced after 48 and 72 h of interaction with *S. aureus*; ‘+’: thickened *P. aeruginosa* colony morphology in interaction with *S. aureus*; ‘−’: no thickened *P. aeruginosa* colony morphology; ‘N/A’: not analyzed.

(b) Bioluminescence measured by photon counting from *P. aeruginosa* DK2-P2M24-2003 with a *pqsA*-lux reporter fusion in monoculture (DK2-Mono), in interaction with *S. aureus* JE2 (DK2-JE2) or the agrC mutant (DK2-agrc) when cultured on LB, TSA or ASM agar surfaces, respectively. *P<0.05 by Tukey’s HSD test compared with DK2-mono. Error bars represent s.d., \( n=3 \).

Figure 3  (a) Interactions between the different *P. aeruginosa* strains, PAO1, DK2-P2M24-2003 (DK2 wt), the DK2-P2M24-2003 *pqsB* mutant (DK2-Tn1) or the PAO601 mutant (DK2-PAO601) and *S. aureus* JE2 when cultured on different agar media, LB, TSA, ASM and under aerobic or anaerobic conditions, respectively. ‘inh’: inhibition of *S. aureus* growth by *P. aeruginosa*; ‘+’: thickened *P. aeruginosa* colony morphology in interaction with *S. aureus*; ‘−’: no thickened *P. aeruginosa* colony morphology; ‘N/A’: not analyzed.
(Supplementary Figure S2). The annotated HAQ molecules corresponded to the molecules detected with increased intensity in the MALDI-TOF IMS analysis of the P. aeruginosa DK2-P2M24-2003 – S. aureus JE2 interaction (Figure 3). Similar to the observation from MALDI-TOF IMS, the signaling and antimicrobial HAQ molecules, PQS and HQNO (that is, m/z 260), respectively were not detected nor identified using MS molecular networking on the P. aeruginosa DK2-P2M24-2003 extracts (Supplementary Figure S2).

The pqsABCDE operon is involved in the biosynthesis of HAQ molecules in P. aeruginosa (Deziel et al., 2004). Thus, in order to confirm an increased production of HAQ molecules by P. aeruginosa DK2-P2M24-2003 during interaction with S. aureus JE2, we constructed a luxCDABE-based reporter gene fusion (Becher and Schweizer, 2000) with the promoter of pqsA. This construct was incorporated into the DK2-P2M24-2003 chromosome. By measuring the bioluminescence from P. aeruginosa DK2-P2M24-2003, we observed an up to threefold increase in pqsA expression in interaction with S. aureus JE2 compared with DK2-P2M24-2003 in monoculture when analyzed on the same media (LB, TSA and ASM, respectively) on which the thickened Pseudomonas colony morphology was observed (Figure 3b). Taking together, these results indicated that the induced HAQ profile is important for the thickened P. aeruginosa DK2-P2M24-2003 colony morphology observed during interaction with S. aureus JE2.

Screen for mechanisms involved in the interaction between P. aeruginosa DK2-P2M24-2003 and S. aureus JE2

A knockout mutation in the gene, PAO601, which previously has been identified to be important for the sensing of S. aureus by P. aeruginosa (Korgaonkar et al., 2013), was constructed in P. aeruginosa DK2-P2M24-2003, however, did not affect the interaction between DK2-P2M24-2003 and S. aureus JE2 (Figure 3a).

Therefore, we established a DK2-P2M24-2003 mariner-based transposon mutant library of 1500

**Figure 4** (a) MALDI-TOF IMS analysis of P. aeruginosa DK2-P2M24-2003 in monoculture (DK2-mono), in interaction with S. aureus JE2 (DK2-JE2) or in interaction with the S. aureus agrC mutant (DK2-agrC) as well as the P. aeruginosa DK2-P2M24-2003 pqsB mutant, Tn1, in interaction with S. aureus JE2 (Tn1-JE2) after 48 h of co-culturing. The m/z distributions of P. aeruginosa molecules are displayed as false color overlays of an optical image. Ion-intensity color scaling indicates a highest production of molecules with m/z 224, 258, 270, 272 and 298, respectively, at the interface between P. aeruginosa DK2-P2M24-2003 and S. aureus JE2. White arrowhead indicates the zone of thickened P. aeruginosa colony morphology. (b) HAQ molecules were annotated from the MS molecular network using MS/MS-based dereplication or fragmentation analysis (indicated by *). Nomenclature, calculated and observed [M+H]⁺ masses, as well as the HAQ series are shown for the different HAQ molecules according to previous studies (Deziel et al., 2004; Heeb et al., 2011).
mutant strains and performed a genetic screen in a spot-interaction setup with *S. aureus* JE2 (Supplementary Figure S4), to further identify genes involved in the *P. aeruginosa* DK2-P2M24-2003 response to *S. aureus* JE2. Four distinct *P. aeruginosa* mutant strains, designated Tn1, Tn2, Tn3 and Tn4, respectively were found, showing no thickened colony morphology in interaction with *S. aureus* JE2 (Figure 4a and Supplementary Figure S4). These mutant strains had the transposon inserted into the *pqsB* gene (Tn1), which is part of the PQS biosynthetic operon, *pqsA-E* (Heeb et al., 2011); a gene encoding a tryptophan permease (Tn2); a gene encoding a putative permease (Tn3); and a gene encoding a UvrD/REP helicase (Tn4), respectively (Supplementary Figure S4). In addition, the *P. aeruginosa* mutant Tn1 did not show the autolysing phenotype of the DK2-P2M24-2003 wild-type strain (Figure 4a and Supplementary Figure S4). MALDI-TOF IMS analysis of *P. aeruginosa* Tn1 revealed a defective production of HAQ molecules, likely because of the *pqsB* gene knockout in this mutant (Figure 4a), which further supported an importance of the induced HAQ profile in DK2-P2M24-2003 for the thickened colony morphology (that is, increased cell density) detected at the interface with *S. aureus* JE2.

In addition to the genetic screen of *P. aeruginosa* DK2-P2M24-2003, the 1920 mutants included in the *S. aureus* JE2 Nebraska Transposon Mutant Library (Fey et al., 2013) were screened in a similar spot-interaction setup with *P. aeruginosa* DK2-P2M24-2003 (Supplementary Figure S5). We identified nine distinct *S. aureus* mutants from this mutant screen, which did not induce the thickened colony morphology in *P. aeruginosa* DK2-P2M24-2003 (Supplementary Figure S5). These mutants were the previously identified strains with the transposon inserted into the *agrC*, *agrB*, *clpP* or *sarA* genes, respectively, (Michelsen et al., 2014) as well as *S. aureus* strains with transposons inserted in *agrA* (NE1532) or in genes encoding different membrane transporter proteins (mutants NE496, NE969 and NE1509, respectively) (Supplementary Figure S5). The molecular interaction between the *S. aureus agrC* mutant and *P. aeruginosa* DK2-P2M24-2003 was further investigated by MALDI-TOF IMS analysis. In contrast to the interaction with the *S. aureus* JE2 wild-type strain, no induction of HAQ molecules was detected in DK2-P2M24-2003 by the presence of the *S. aureus agrC* mutant, which instead resembled the autolysing HAQ profile of the DK2-P2M24-2003 monoculture (Figure 4a). In addition, the *pqsA* expression profile in *P. aeruginosa* DK2-P2M24-2003 during interaction with *S. aureus agrC* was similar to that of DK2-P2M24-2003 in monoculture (Figure 3b), which suggests that a functional *agr* system in *S. aureus* is required for inducing the distinct HAQ profile and thickened colony morphology in *P. aeruginosa* DK2-P2M24-2003.

**Discussion**

The importance of understanding interspecies interactions in complex polymicrobial infections is manifested by enhanced antibiotic resistance or persistency of bacterial pathogens at the infection site. One example is the interaction between the opportunistic human pathogens *P. aeruginosa* and *S. aureus* that may cause more severe infections when found together compared with when present alone (Peters et al., 2012; Hubert et al., 2013; Pastar et al., 2013). However, the nature of long-term interactions during co-existence of these two species (as occurs in chronic polymicrobial infection) has proven difficult to study in *vitro*, due to *S. aureus* growth suppression by *P. aeruginosa* exoproducts (Duan et al., 2003; Hoffman et al., 2006; Mitchell et al., 2010; DeLeon et al., 2014). Here, we postulate differences in strains that form polymicrobial infections contribute to this. Accordingly, we observed an effective killing of *S. aureus* JE2 by the laboratory reference strain *P. aeruginosa*
PAO1 when co-cultured on agar surfaces. However, in contrast to PAO1, suppression of *S. aureus* JE2 growth was not observed by the human host-adapted *P. aeruginosa* strain, DK2-P2M24-2003. This co-existence of DK2-P2M24-2003 and *S. aureus* JE2 was reproducible on different agar media, including ASM, and under aerobic and anaerobic growth conditions, which thereby allowed us to explore the molecular-genetic basis of co-culture interactions between these strains.

By combining molecular genetics with MALDI-TOF IMS and MS molecular networking, we observed a significant divergent metabolic profile between *P. aeruginosa* PAO1 and DK2-P2M24-2003. Although *P. aeruginosa* PAO1 produced pyocyanin, rhamnolipids and HQNO, which are all part of the antimicrobial circuitry of *P. aeruginosa* (Hoffman et al., 2006; Strateva and Mitov, 2011), these antimicrobials were not detected in *P. aeruginosa* DK2-P2M24-2003, and most likely explain why DK2-P2M24-2003 and *S. aureus* JE2 are able to co-exist. It has been well established that *P. aeruginosa* evolves during long-term infections in human hosts (Smith et al., 2006; Marvig et al., 2013). Loss-of-function mutations in the *lasR* gene are commonly detected during *P. aeruginosa* adaptation to the CF airways (Smith et al., 2006; D’Argenio et al., 2007), which encodes a central quorum sensing-dependent transcriptional activator of multiple virulence genes (Gallagher et al., 2002; D’Argenio et al., 2007). In addition, LasR regulates the expression of *pqsH*, which is involved in the biosynthesis of HAQ molecules (that is, responsible for the conversion of the precursor HHQ to the signaling molecule, PQS; Deziel et al., 2004). Together with other regulatory mutations, the *lasR* loss-of-function mutation has been detected in the human host-adapted *P. aeruginosa* DK2 lineage (Yang et al., 2011; Damkiaer et al., 2013) and is also present in *P. aeruginosa* DK2-P2M24-2003 (Michelsen et al., 2014). Therefore, this mutation could serve as a contributing factor for the divergent metabolic profile observed in DK2-P2M24-2003 compared to PAO1. Besides LasR our previous study with a *lasR*
mutation in a PAO1 background clearly stated that additional mutations could contribute as well (Michelsen et al., 2014). A characteristic phenotype of P. aeruginosa lasR mutants is visible autolysis and an iridescent metallic sheen coverage of colonies (D’Argenio et al., 2007). This phenotype has been attributed to an increased ratio of ‘Series A congeners’ (for example, HHQ) to ‘Series B congeners’ (for example, PQS) of HAQ molecules (D’Argenio et al., 2007; Gupta and Schuster, 2012). Autolysis and metallic sheen coverage was also observed of the DK2-P2M24-2003 colony. However, besides an increased HHQ:PQS ratio, additional Series A and D congeners (NHQ, UHQ and derivatives, respectively) were detected by MALDI-TOF IMS and MS molecular network analysis, which suggest a more complex autolysing HAQ profile in this strain.

Previous work has reported that P. aeruginosa responds to the S. aureus cell wall components, peptidoglycan and GlcNAc, with an increased production of virulence factors, and thereby further suppressing S. aureus during interaction (Korgaonkar and Whiteley, 2011; Korgaonkar et al., 2013). A strikingly different response to S. aureus was observed by P. aeruginosa DK2-P2M24-2003 in this study. Instead of an increased production of virulence factors, the presence of S. aureus JE2 induced a distinct HAQ profile of accumulated series A and D congeners in DK2-P2M24-2003, thereby substituting the autolysing HAQ profile at the P. aeruginosa–S. aureus interface. Thus, the distinct HAQ profile in DK2-P2M24-2003 at the interface with S. aureus JE2 could explain the observed thickened colony morphology, which we have previously identified as a zone with increased Pseudomonas cell density (Michelsen et al., 2014). This model is summarized in Figure 6. Our model was further supported by a genetic screen of 1500 P. aeruginosa DK2-P2M24-2003 transposon mutants in interaction with S. aureus JE2. Here we identified two mutations, in a gene encoding a tryptophan permease and the pqsB gene, respectively that no longer responded to S. aureus. Tryptophan provides a precursor for HAQ molecules (Farrow and Pesci, 2007; Heeb et al., 2011), whereas pqsB is directly involved in the biosynthesis of HAQs (Deziel et al., 2004; Heeb et al., 2011). The DK2-P2M24-2003 pqsB mutant (Tn1) showed a distinct smooth colony morphology with no autolysis, which could be explained by the abolished HAQ production and thereby no autolysing HAQ profile in this strain as revealed by MALDI-TOF IMS. In addition to the effect on P. aeruginosa itself, the HAQ molecules produced by DK2-P2M24-2003 were associated with a protection of S. aureus from killing by tobramycin, an antibiotic commonly used in CF therapy.

Figure 6 Model for P. aeruginosa DK2-P2M24-2003–S. aureus JE2 proto-cooperation and the importance of the P. aeruginosa produced HAQ molecules for this interaction. According to the model, genetic adaptation during long-term infection is manifested by metabolic divergence in DK2-P2M24-2003 (DK2) resulting in an autolysing HAQ profile (HAQ profile A) and distinct colony morphology as well as the ability to co-exist with S. aureus (S. a.). In interaction with S. aureus, a thickened colony morphology (i.e., increased cell density) is observed in DK2-P2M24-2003 explained by an induction of a second HAQ profile (HAQ profile B). In addition, HAQ molecules produced by DK2-P2M24-2003 mediate a protection of S. aureus from the killing effect by tobramycin frequently used in CF therapy.
It became clear that peptidoglycan and GlcNAc were not involved in the induced HAQ profile in *P. aeruginosa* DK2-P2M24-2003 by *S. aureus* JE2, since a knockout of the sensing mechanism, PAO601 (Korgaonkar et al., 2013), in *P. aeruginosa* DK2-P2M24-2003 did not eliminate the thickened colony morphology. The genetic background of *S. aureus* JE2 has been used as a host for creating a well-characterized sequence-defined transposon mutant library, that is the Nebraska Transposon Mutant Library (NTML), to investigate *S. aureus* biology and pathogenesis (Fey et al., 2013). We have previously identified the genes, agrC, agrB, clpP and sarA, in *S. aureus* JE2 to be involved in the induction of the DK2-P2M24-2003 thickened colony morphology (Michelsen et al., 2014). The involvement of these genes was also confirmed in this study by a genetic screen with the full *S. aureus* JE2 NTML consisting of 1952 mutant strains. MALDI-TOF IMS analysis of the interaction between DK2-P2M24-2003 and the *S. aureus* agrC mutant compared with *S. aureus* JE2 revealed no induction of the distinct HAQ profile in DK2-P2M24-2003, which could explain why the thickened *Pseudomonas* colony morphology was not observed in this interaction. Instead an autolysing HAQ profile resembling the profile in DK2-P2M24-2003 monoculture was found in the *S. aureus* agrC interaction. Our genetic screen identified additional membrane transporter proteins, suggesting further the involvement of *S. aureus* extracellular molecules as agents for HAQ profile modifications in *P. aeruginosa*.

In summary, by combining molecular genetics and MALDI-TOF IMS analysis we demonstrate here a difference in the production of antimicrobial and signaling (HAQ) molecules between the laboratory model strain, *P. aeruginosa* PAO1, and the human host-adapted strain, *P. aeruginosa* DK2-P2M24-2003. The metabolic divergence explains their distinct interaction patterns, that is, antagonistic versus commensal-like, respectively with *S. aureus* JE2. The HAQ profile in *P. aeruginosa* DK2-P2M24-2003 was further modulated during interaction with *S. aureus* JE2, which facilitated a proto-cooperative relationship between the two bacteria. Thus, our results emphasize the importance of HAQ molecules in this interspecies interaction (as summarized in Figure 6). In the context of long-term infections, our finding of strain diversity cautions against generalizing conclusions of interactions between bacterial pathogens, which are based on experimental models with one or a few selected strains.

**Conflict of Interest**

The authors declare no conflict of interest.

**Acknowledgements**

We thank Martin Saxtorp Bojer (University of Copenhagen, Denmark) for help with screening the *S. aureus* Nebraska mutant library and Sara Dyhrberg (Technical University of Denmark, Denmark) for help with creating and screening the *P. aeruginosa* DK2-P2M24-2003 mutant library, respectively. In addition, we thank Tal Luzzatto Knaan (University of California at San Diego, USA) for help with running the LC-MS/MS analysis. Morten Sommer (Technical University of Denmark, Denmark) is acknowledged for providing access to an anaerobic chamber. The PAO601 deletion plasmid was kindly provided by Justine Murray and Marvin Whiteley (University of Texas, USA), and the pCTX:pgsA-lux reporter plasmid was kindly provided by Paul Williams (The University of Nottingham, UK). Funding for this study was provided by an operating grant from the Villum Foundation to LJ (VKR023113). The Novo Nordisk Foundation supported HKJ as a clinical research stipend. The Aase & Ejnar Danielsens Foundation (ref. no. 10-001120) and the Augustinus Foundation (ref. no. 13-4656) are acknowledged for travel grants to CFM. We further acknowledge Bruker and NIH Grant GMS10RR029121 for the support of the shared instrumentation infrastructure that enabled this work.

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Supplementary Information accompanies this paper on The ISME Journal website (http://www.nature.com/ismej)