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1 **Alginate Oligosaccharide-Induced Modification of the *lasI-lasR* and *rhlI-rhlR***

2 **Quorum Sensing Systems in *Pseudomonas aeruginosa***

3
4 **Short title:** OligoG CF-5/20 affects Quorum Sensing in *P. aeruginosa*

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22 **ABSTRACT**

23 *Pseudomonas aeruginosa* plays a major role in many chronic infections. Its ability to readily
24 form biofilms contributes to its success as an opportunistic pathogen and its
25 resistance/tolerance to antimicrobial/antibiotic therapy. A low molecular weight alginate
26 oligomer (OligoG CF-5/20), derived from marine algae, has previously been shown to impair
27 motility in *P. aeruginosa* biofilms and disrupt pseudomonal biofilm assembly. As these
28 bacterial phenotypes are regulated by quorum sensing (QS), we hypothesized that OligoG
29 CF-5/20 may induce alterations in QS signalling in *P. aeruginosa*. QS regulation was studied
30 using *Chromobacterium violaceum* CV026 biosensor assays that showed a significant
31 reduction in acyl homoserine lactone (AHL) production following OligoG CF-5/20 treatment
32 ($\geq 2\%$; $P < 0.05$). This effect was confirmed by liquid chromatography/mass spectrometry
33 (LC/MS) analysis of C4-AHL and 3-oxo-C12-AHL production ($\geq 2\%$; $P < 0.05$). Moreover,
34 quantitative PCR (qPCR) showed that reduced expression of both the *las* and *rhl* systems
35 was induced following 24 h treatment with OligoG CF-5/20 ($\geq 0.2\%$; $P < 0.05$). Circular
36 dichroism (CD) spectroscopy indicated that these alterations were not due to steric
37 interaction between the AHL and OligoG CF-5/20. Confocal laser scanning microscopy and
38 COMSTAT image analysis demonstrated that OligoG CF-5/20 treated biofilms had a dose-
39 dependent decrease in biomass which was associated with inhibition of eDNA synthesis
40 ($\geq 0.5\%$; $P < 0.05$). These changes correlated with alterations in extracellular production of
41 the pseudomonal virulence factors pyocyanin, rhamnolipids, elastase and total protease
42 ($P < 0.05$). The ability of OligoG CF-5/20 to modify QS signalling in *P. aeruginosa* PAO1 which
43 may influence critical downstream functions, such as virulence factor production and biofilm
44 formation.

45

46 INTRODUCTION

47 *Pseudomonas aeruginosa* is an opportunistic and nosocomial human pathogen, which can
48 cause extensive tissue damage through the production of virulence factors and toxins e.g.
49 pyocyanin and proteases (1). The dynamic genome of *P. aeruginosa* is highly adaptable,
50 enabling it to adjust to a wide range of environmental conditions (2, 3). This versatility
51 allows it to colonise diverse physiological niches including the respiratory tract, genito-
52 urinary tract and wounds.

53 The sodium alginate oligomer OligoG CF-5/20, produced from the brown seaweed
54 *Laminaria hyperborea*, has been shown to potentiate (enhance) antimicrobial efficacy,
55 perturb multidrug resistant bacteria (4-7) and inhibit biofilm formation in a broad range of
56 organisms (8). Furthermore, it has also previously been shown to inhibit swarming and
57 “twitching” motility, exhibiting a significant effect on bacterial flagella- and pilus-mediated
58 chemotaxis (4, 5). Although OligoG CF-5/20 is known to have cation-chelating properties,
59 the precise mechanism of action in mediating this diverse range of effects remains unclear.

60 Quorum sensing (QS) is a cell density-dependent communication system between
61 local populations of bacterial cells, regulating and coordinating their gene expression using
62 diffusible signalling molecules (9, 10). In Gram-negative pathogens (in particular *P.*
63 *aeruginosa*), QS is regulated by acylated homoserine lactones (AHLs) produced by a
64 transcriptional regulator based on the LuxR/LuxI-type QS system that was first characterized
65 in *Vibrio fischeri* (11). The regulation of QS in *Pseudomonas* spp. is both subtle and complex
66 (12) (**Fig 1**). *P. aeruginosa* has four QS systems, two acyl-homoserine lactone (AHL)- and one
67 2-heptyl-3-hydroxy-4-quinolone- mediated system known as the *Pseudomonas* quinolone
68 signal (PQS) system and the more recently identified integrated QS system (IQS) (13). The
69 AHL systems in *P. aeruginosa* are known as the *lasI-lasR* and *rhlI-rhlR* systems and the

70 transcriptional regulators LasR and RhlR regulate production of the signalling molecules
71 (autoinducers) *N*-(3-oxododecanoyl)-L-AHL (3-oxo-C12-AHL) and *N*-butyryl-L-AHL (C4-AHL)
72 respectively. The QS system in *P. aeruginosa* is regulated by an inter-linked, hierarchical
73 mechanism where *lasR*/3-oxo-C12-AHL induces expression of *lasI*, as well as *rhlR/rhlI* and
74 the PQS system. Disruption of the IQS signal can effectively paralyze the PQS and *rhl* QS
75 systems (14). A number of additional regulators of this QS system exist, at both
76 transcriptional and post-transcriptional levels, including the global activator GacA and
77 regulator Vfr (13). In addition, QS also regulates key cellular processes such as promotion of
78 eDNA release, RNA transcription and translation, cellular division and amino acid synthesis.

79 Global gene expression analysis of the QS systems in *P. aeruginosa* has shown that 6-
80 10% of the genome is regulated through the *las* and *rhl* systems (12, 15). QS plays a role in
81 swarming motility, biofilm development and expression of antibiotic efflux pumps (16) as
82 well as virulence factor production. *P. aeruginosa* QS-activated virulence factors include
83 proteases e.g. elastase, pyocyanin, lectins, rhamnolipids, and toxins. Such virulence factors
84 can affect biofilm formation and maintenance, as well as swarming motility. Their
85 regulation is complex, with numerous intrinsic and environmental factors involved such as
86 cell-number, composition of the extracellular polymeric substance (EPS), matrix density and
87 oxygen availability. However, the production of pyocyanin, proteases and rhamnolipids
88 reflects optimal QS signalling (17). Pyocyanin is a blue secondary metabolite produced by *P.*
89 *aeruginosa* evident in the sputum of infected cystic fibrosis patients (18). As a zwitter ion,
90 at a physiological pH, it can readily penetrate biological membranes, inducing host cell
91 necrosis and inflammation, both directly (e.g. IL-8) and indirectly via cellular damage (19).
92 Importantly, in the context of biofilm persistence *in vivo*, pyocyanin induces the deposition
93 of extracellular DNA (eDNA) which is a major component of biofilm EPS, being essential for

94 biofilm formation and stability (20). Production of both pyocyanin and eDNA is mediated by
95 AHL and PQS molecules, as well as by flagella and type IV pili (21, 22).

96 The regulation of QS in *P. aeruginosa* is sensitive to, and modulated by, growth and
97 environmental conditions, which impact significantly on the timing of *lasI*, *lasR*, *rhlI* and *rhlR*
98 expression (9, 23). The complexity of this QS system in *P. aeruginosa* is thought to be one of
99 the main factors responsible for its selective adaption and environmental versatility (24).
100 The QS system also affords selective “fitness” advantages in human disease. For example,
101 QS signalling molecules produced by *P. aeruginosa* are also recognised by *Burkholderia*
102 *cepacia*, resulting in synergistic interactions in mixed-species biofilms (25), thereby
103 potentially increasing the virulence of both species in the cystic fibrosis lung. Moreover, the
104 expression of AHL and PQS molecules has been shown to affect the mammalian host-
105 pathogen response (26) with 3-oxo-C12-AHL and PQS having anti-inflammatory and pro-
106 apoptotic effects on murine fibroblasts and human lung epithelial cells at concentrations
107 <10 μ M (27).

108 Rhamnolipids are bacterial glycolipid surfactants, composed of a rhamnose glycosyl
109 head and a 3-(hydroxyalkanoyloxy) alkanolic acid fatty acid tail. Rhamnolipid expression
110 plays a crucial role in microbial motility, hydrophobic uptake and biofilm formation on host
111 surfaces. Proteases (including the zinc-dependent metalloproteinase elastase) also play an
112 important role in the pathogenicity of *Pseudomonas* spp. facilitating invasion and
113 destruction of host tissue (28). Rhamnolipid production is regulated by the *P. aeruginosa*
114 quorum sensing regulator, *rhlR*, whilst elastase and protease activities are regulated by the
115 *lasIR* system.

116 QS inhibitors that impede QS pathways in microorganisms are an attractive target
117 for antimicrobial therapy development. We hypothesized that the antibiotic susceptibility,

118 motility and biofilm-assembly modifications induced in *P. aeruginosa* by OligoG CF-5/20
119 might relate to alterations in the regulation of *lasI-lasR* and *rhlI-rhlR* and studied this *in vitro*.

120

121

122 RESULTS

123 **OligoG CF-5/20 inhibits growth of *P. aeruginosa* PAO1 and reduces violaceum**
124 **induction and inhibition of the *Chromobacterium violaceum* biosensor CV026.** The effect
125 of OligoG CF-5/20 on the growth of *P. aeruginosa* PAO1 was examined using growth curves.
126 OligoG CF-5/20 at concentrations of $\geq 2\%$ was found to significantly reduce the growth *P.*
127 *aeruginosa* PAO1 (Minimum significant difference, MSD=0.154; $P < 0.01$; **Fig 2A**). This growth
128 curve data was used to determine the time-points (12, 18, 24 and 30 h) employed in the
129 subsequent time-course study.

130 A time-course study was undertaken using induction or inhibition of violaceum in the
131 *Chromobacterium violaceum* biosensor strain CV026 as an indicator of QS signalling (C4-AHL
132 and 3-oxo-C12-AHL respectively), following treatment with OligoG CF-5/20 (**Fig 2B, 2C and**
133 **2D**). Untreated controls showed distinct differences in *P. aeruginosa* PAO1 AHL production
134 with time, which were maximal at 18 h for C4-AHL induction and 24 h for 3-oxo-C12-AHL
135 inhibition. OligoG CF-5/20 treated samples showed a reduction in C4-AHL, particularly at 18
136 and 24 h which was significant from 0.2% OligoG CF-5/20 and at 30 h from 2% (**Fig 2B and**
137 **2C**). Measurement of zones of clearing indicated that OligoG CF-5/20 had less of an effect
138 on 3-oxo-C12-AHL inhibition when compared to C4-AHL induction (zone of coloration).
139 Violaceum inhibition was significantly reduced at the 24 h time point, at all OligoG CF-5/20
140 concentrations, in comparison to the control ($P < 0.05$; **Fig 2B and 2D**).

141 **Homoserine lactones C4-AHL and 3-oxo-C12-AHL can be detected using LC/Mass**
142 **Spectrometry.** For a more accurate determination of AHL concentrations, preliminary
143 analysis of the AHLs, C4-AHL (Fig 3A) and 3-oxo-C12-AHL (**Fig 3B**) using LC/MS (**Fig 3C**) was
144 undertaken from an initial time course following PAO1 growth at 18, 24 and 30 h. LC/MS
145 demonstrated a time-dependent decrease in C4-AHL (**Fig 3D**) which was significantly
146 different at 30 h ($P<0.05$). Conversely, levels of 3-oxo-C12-AHL were considerably lower (up
147 to 6-fold) and did not demonstrate time-dependent decreases.

148 **LC/Mass Spectrometry shows time-dependent decreases in AHL production following**
149 **OligoG CF-5/20 treatment.** A subsequent time-course of OligoG CF-5/20-treated PAO1
150 (grown at 12, 18, 24 and 30 h) demonstrated significant reductions in C4-AHL production at
151 all time-points ≥ 2 % OligoG (**Fig 4A**), the exception being 18 h at 2% which was not
152 significant. A similar significant reduction was seen for 3-oxo-C12-AHL (**Fig 4B**; $P<0.05$) in
153 comparison to the untreated control (except for 18 and 24 h at 2%), although much lower
154 overall levels were detected (up to 29.5 mg/L) compared to C4-AHL (up to 102.3 mg/L) (**Fig**
155 **4**).

156 **OligoG CF-5/20 reduces extracellular virulence factor production in *P. aeruginosa***
157 **PAO1.** As the biosensor analysis showed that OligoG CF-5/20 affected bacterial signalling,
158 the production of virulence factors, regulated in *P. aeruginosa* PAO1 by quorum sensing,
159 was investigated. OligoG CF-5/20 ($\geq 0.2\%$) significantly reduced the amount of pyocyanin at
160 all time points ≥ 18 h (**Fig 5A**; $P<0.05$). However, for rhamnolipid production a significant
161 reduction was only observed at 18 h (for all OligoG CF-5/20 concentrations tested) or 24 h
162 (at $\geq 2\%$ OligoG CF-5/20; $P<0.05$) with no significant change seen at either 12 or 30 h (**Fig**
163 **5B**). In contrast, a significant reduction in total protease (**Fig 5C**) and elastase (**Fig 5D**)
164 production was seen at $\geq 0.2\%$ OligoG CF-5/20 and then only at the 24 h time point ($P<0.05$).

165 **OligoG CF-5/20 reduces expression of quorum sensing genes.** Phenotypic studies were
166 confirmed by genotypic analysis using qPCR. Temporal expression of QS genes following
167 OligoG CF-5/20 treatment was observed (**Fig 6**). Significant reductions in expression of *lasI*,
168 *rhII* and *rhIR* at 12 h (**Fig 6A**), *lasI*, *lasR* and *rhIR* at 18 h (**Fig 6B**) and *rhIR* at 24 h (**Fig 6B and C**)
169 respectively; $p < 0.05$) were evident, which for *lasI*, *rhII* and *rhIR* at 12 h and *lasR* at 18 h,
170 were significant for all three concentrations of OligoG tested. No significant effect of OligoG
171 CF-5/20 on AHL expression was detected by qPCR at the 30 h time point (Fig 6D).

172 **CLSM shows that OligoG CF-5/20 reduces production of eDNA and behaves similarly**
173 **to QS inhibitors against biofilms of *P. aeruginosa* PAO1.** CLSM imaging of TOTO-1 nucleic
174 acid-stained 24 h biofilms demonstrated that OligoG CF-5/20 ($\geq 0.5\%$) induced a significant
175 decrease in eDNA production after treatment ($P > 0.05$) (**Fig 7 and 8**). This was evident in
176 biofilms grown in the presence of OligoG (biofilm formation studies) and for 24 h biofilms
177 subsequently treated with OligoG for 24 h (biofilm disruption studies). Although the CLSM
178 imaging did not appear to show a dose-dependent decrease in eDNA production (**Fig 7**). A
179 dose-dependent decrease was, however, evident at $\geq 2\%$ OligoG in direct analysis of treated
180 biofilm samples (**Fig 8**).

181 The structural alterations induced in biofilms by OligoG CF-5/20 were compared to the
182 effects of the QS inhibitors, 2(5H)-furanone and N-decanoyl cyclopentylamide (C10-CPA)
183 (29, 30) using LIVE/DEAD staining (**S1A Fig**) showing that the effects of OligoG resembled the
184 inhibition induced by the other AHL-dependent quorum sensing inhibitors tested (**S1B and**
185 **S1C Fig**).

186 **Circular dichroism showed that OligoG CF-5/20 does not interact directly with AHLs.**
187 Circular dichroism (CD) spectroscopy rapidly determines protein and polypeptide secondary
188 structure, and has previously been shown to give excellent comparability to ^1H NMR

189 spectroscopy in determining alginate M/G residue ratios (31). CD was used here to confirm
190 that the effects of OligoG CF-5/20 were not due to simple physical interaction with the AHL
191 molecules. The CD signal of OligoG CF-5/20 titrated with C4-AHL or 3-oxo-C12-AHL showed
192 no substantial change (**S2 Fig**). The minima of the spectra around 210 nm, revealing the
193 orientation of the alginate carboxy groups and thus directly indicative of the conformation
194 of OligoG CF-5/20 (32), appeared unaffected by either of the two AHLs. The ellipticities
195 recorded at 208 nm (after addition of AHLs at their maximum concentrations over ~1h)
196 suggested that kinetic effects were not responsible for the absence a signal (insets in **S2 Fig**).

197

198

199 **DISCUSSION**

200 This study confirms that OligoG CF-5/20 affects global regulatory QS signalling in *P.*
201 *aeruginosa* PAO1 as was hypothesised following the original observations on bacterial
202 motility (4, 7). The biosensor strain *C. violaceum* CV026 demonstrated that OligoG CF-5/20
203 reduced C4-AHL and 3-oxo-C12-AHL production in *P. aeruginosa* PAO1, (as seen by QS
204 induction and inhibition respectively) in a time- and dose-dependent manner. This was
205 further confirmed by LC/MS and qPCR, and that OligoG CF-5/20 also had a significant effect
206 on the production of other virulence factors such as pyocyanin, rhamnolipid, total protease,
207 and elastase. The dose-dependent nature of the observed inhibition suggested that OligoG
208 does not simply act as an AHL receptor antagonist by binding to the receptor, thereby
209 effectively “blocking” all AHL binding. Furthermore, the CD analysis excluded the possibility
210 that the observed alterations in QS signalling molecules and virulence factor expression
211 were the result of simple, steric interactions between the oligosaccharide and the AHL
212 signalling molecules in the biofilm system.

213 The LC/MS data demonstrated the complex, time-dependent nature of virulence factor
214 production by *P. aeruginosa* with optimal (maximum) production of both AHLs (C4-AHL and
215 3-oxo-C12-AHL) at 12 h (equivalent to late exponential/early stationary growth phase).
216 These findings are in keeping with previous studies, which showed that whilst AHL
217 production peaks during exponential growth, C4-AHL levels decrease as stationary phase is
218 attained (12). The finding here, that 3-oxo-C12-AHL levels remained relatively constant if
219 the medium was sufficiently buffered to avoid alkali-mediated lactonolysis, is consistent
220 with those of Yates et al (33).

221 Las and Rhl are regulated by the LuxR family of transcriptional regulators (lasR and
222 RhlR), making their expression extremely sensitive to environmental conditions e.g. hypoxia,
223 pH and hydrodynamic shear (which are important in biofilm infections). AHL production has
224 been shown to vary significantly under different environmental growth conditions,
225 especially under nutrient-limitation, with higher AHL expression observed in minimal or
226 diluted media, when compared to nutrient media (9). In addition, both *las* and *rhl* were
227 expressed earlier (in early to mid-log phase) in nutrient-limited media compared to early
228 stationary phase in nutrient media. Interestingly, these phenomena were unrelated to cell-
229 density, which is usually considered a pre-requisite for QS expression. Comparing 46
230 different experimental conditions, Duan and Surette (9) showed that the individual
231 dominance of the *las* and *rhl* system reflected environmental conditions. LasR mutants are
232 commonly found in both clinical and environmental isolates, indicating autonomous
233 regulation of these integrated systems (34, 35). Transcription of Las and Rhl may also occur
234 independently, permitting further “fine-tuning” of each system *in vivo*. This may, in part,
235 explain the independent (and distinct) responses to OligoG CF-5/20 treatment observed in
236 C4-AHL and 3-oxo-C12-AHL production in the time-course experiments.

237 Swarming is a complex form of motility, and is consequently influenced by a large
238 number of different genes. Rhamnolipids are known to modulate the intricate swarming
239 motility patterns of *P. aeruginosa* (36). Therefore, it was perhaps unsurprising that, as
240 OligoG CF-5/20 was previously shown to affect swarming motility of *Proteus* and *P.*
241 *aeruginosa* (4, 7 respectively), that rhamnolipid production should also be affected by
242 OligoG CF-5/20. Importantly, QS regulation of rhamnolipids and swarming motility
243 contribute to *P. aeruginosa* biofilm dispersal, and therefore help to explain the dramatic
244 effect of OligoG CF-5/20 on both biofilm formation and disruption of established biofilms
245 previously described (4, 7). In support of this notion, a range of mini-Tn5 insertion,
246 “swarming-negative” *P. aeruginosa* mutants exhibited impaired biofilm formation (37),
247 confirming the link between both phenotypes. The finding here, of more significant
248 inhibition of pyocyanin and rhamnolipid production by OligoG CF-5/20 (when compared to
249 the effects on elastase and total protease production) may relate to differential expression
250 of the different QS pathways. The three most characterised QS signalling systems in *P.*
251 *aeruginosa* are believed to be sequentially activated in “nutrient-rich” media, with LasR
252 sitting at the top of the temporal cascade, and AHLs (*las* and *rhl*) being released in early- and
253 PQS in late-exponential phases of growth (38).

254 Las and Rhl control both biofilm formation and expression of virulence factors in *P.*
255 *aeruginosa* (11). The LasR–3-oxo-C12-AHL complex activates transcription of target genes
256 including those encoding virulence factors such as elastase, proteases, and exotoxin. In
257 contrast, RhlR–C4-AHL activates target genes, including those encoding elastase, proteases,
258 pyocyanin, and siderophores (39). There appears to be a considerable overlap in the
259 virulence factors these regulons control (9). The finding that the inhibition of
260 pyocyanin/rhamnolipid production was more evident throughout the time-course of the

261 experiment than that of protease and elastase, may be a reflection of OligoG differentially
262 affecting the Rhl QS system, to a greater extent than the Las system.

263 The intrinsically high levels of antimicrobial resistance typically seen in *P. aeruginosa*
264 are due to its low permeability and multidrug efflux systems, four of which contribute
265 significantly to innate antibiotic resistance. Khan et al. (4) demonstrated that OligoG CF-
266 5/20 increased potentiation of antibiotics against MDR bacteria (up to 128 fold). The
267 authors established that this did not relate simply to permeabilisation of the pseudomonal
268 lipopolysaccharide cell-wall or targeting of the multi-drug efflux pump MexAB-OrpM,
269 suggesting that the QS inhibition observed here with OligoG CF-5/20, involves a mechanism
270 other than inhibition of AHL efflux pumps in *P. aeruginosa*. Instead, the OligoG CF-5/20-
271 induced reduction in AHL production more likely reflects an effect further “upstream” e.g.
272 on bacterial two-component system (TCS) signal transduction pathways (40) by which
273 means bacteria are able to detect and produce a response to environmental changes.

274 TCSs are comprised of an inner membrane-bound “sensor” generally a histidine kinase
275 (which detects environmental stimuli) and a response regulator (which modulates the
276 response). There are many TCSs in *P. aeruginosa*, and these are recognized to play a role in
277 regulating bacterial virulence, biofilm formation and antibiotic susceptibility; factors known
278 to be influenced by OligoG CF-5/20, although the precise links between TCSs and QS are still
279 poorly understood (41). At least three TCSs (BfiSR, MifR and BfmSR) are thought to be
280 involved in the activation of biofilm formation (42). The recently-published
281 BfmS/BfmR/RhIR TCS has been shown to be key to regulation of the *rhl* QS pathway in *P.*
282 *aeruginosa* (43) modulating expression of biofilm formation and virulence. Interestingly,
283 deletion of the sensor gene *BfmS* was shown to cause inhibition of the *rhl* QS system, with
284 *BfmR* playing a central role in biofilm maturation. In addition, it has also recently been

285 suggested that BfmRS is involved the development of virulence during bacterial adaptation
286 to the CF lung (43, 44). Interestingly, AlgR (another key *Pseudomonas aeruginosa*
287 transcriptional response regulator) also appears to play an essential role in bacterial
288 virulence and motility (45).

289 The chemical composition of the EPS represents a formidable “barrier” to diffusion and
290 contributes to resistance to antibiotic and antimicrobial therapy (46). The physical
291 disruption of the biofilm structure and alterations in eDNA distribution within the
292 pseudomonal biofilms (induced by OligoG) was, perhaps, unsurprising as QS and pyocyanin
293 have an important regulatory role in eDNA synthesis. Pyocyanin induces eDNA release, with
294 biofilms formed by QS mutants known to possess reduced eDNA compared to wild-type
295 biofilms and to be more susceptible to chemical disruption (21, 47). Our results further
296 confirm these findings, where OligoG treatment of *P. aeruginosa* PAO1 resulted in
297 significant decreases in pyocyanin and eDNA production

298 Virulence-targeted anti-bacterials, which effectively ‘disarm’ pathogenic bacteria, have
299 received considerable attention (48) although many have proved to be short-lived due to
300 issues with toxicity and the acquisition of bacterial resistance. Resistance to furanone in *P.*
301 *aeruginosa* can be selected for *in vitro*, as well as being found in clinical isolates (49). In
302 contrast to many of the previously described therapeutic modalities, OligoG, which targets
303 bacterial virulence as a QS antagonist, shows considerable promise. Phase I and Phase IIa
304 human studies failed to demonstrate toxicity. Moreover, extended *in vitro* serial passage in
305 the presence of OligoG, has failed to demonstrate the acquisition of bacterial resistance (4).

306 As QS inhibitors target specific pathogenicity traits such as virulence determinants,
307 there has been considerable interest in their use as use as novel anti-infective therapies (50)
308 both by screening for novel compounds (51) and by targeted synthesis of new ligands (52).

309 Similar to OligoG, the QS inhibitors, furanone and C10-CPA have previously been shown to
310 impede AHL-mediated QS in *P. aeruginosa* leading to an altered biofilm architecture,
311 reduced virulence factor production, as well as enhanced bacterial detachment and
312 antibiotic susceptibility (53, 30 respectively). Predictably, the QS inhibition effects seen with
313 OligoG appear to more closely resemble those of the C10-CPA tested here, interfering as it
314 does with both the *las* and *rhl* QS systems, unlike furanone, which was predominantly found
315 to perturb the *las* system. The dose-response effects and effects on bacterial growth
316 observed in this study suggest that although OligoG CF-5/20 does not act as a true QS
317 inhibitor, it does act as a QS antagonist, affecting signalling pathways in *P. aeruginosa*, with
318 expression of Las and Rhl QS pathways altered in a dose-dependent manner following
319 OligoG CF-/20 treatment. This also proposes a mechanistic rationale for the previously-
320 described anti-biofilm properties of this novel antimicrobial agent that is currently in human
321 clinical trials.

322

323

324 MATERIALS AND METHODS

325 **Alginate oligosaccharides.** The low molecular weight alginate oligosaccharide, OligoG
326 CF-5/20 (Mn = 2800) used in the study was prepared, purified and characterized as
327 previously described (4).

328 **Growth curves.** Overnight cultures of *P. aeruginosa* PAO1 grown in tryptone soya broth
329 at 37°C, 120 rpm were diluted (1:100) in Mueller-Hinton (MH) broth ± OligoG CF-5/20 (0.2%,
330 2% and 10%). The growth of *P. aeruginosa* PAO1 was monitored over 48 h, aerobically at
331 37°C. Absorbance (OD₆₀₀) values taken every hour in a in a FLUOstar Optima plate reader

332 (BMG LABTECH). A one-way ANOVA using Tukey-Kramer post-test and the minimum
333 significant difference generated.

334 ***Chromobacterium violaceum* CV026 biosensor strain.** *C. violaceum* CV026 is unable to
335 produce the purple pigment violacein without an external source of AHLs; therefore,
336 violacein production is induced by AHLs that are C4-C8 in length, whereas inhibition of
337 violacein production can also occur using AHLs of a longer carbon chain length (C10-C14).
338 Both *P. aeruginosa* AHLs can, therefore, be detected using the *C. violaceum* CV026 strain:
339 C4-AHL by induction of violacein production, and 3-oxo-C12-AHL by inhibition.

340 **Acyl-homoserine lactone (AHL) extraction.** Cell free supernatants were collected and
341 equivalent volumes of ethyl acetate (acidified by supplementing with 0.5% formic acid)
342 added. Following mixing for 30 s, the phases were allowed to separate and the top layer
343 collected, this was repeated three times. The combined ethyl acetate fractions were
344 evaporated and the precipitate was resuspended in 1 ml of distilled H₂O (54). Samples were
345 used immediately or freeze-dried and stored at -20°C until required.

346 **Screening of AHL extracts using CV026 induction and inhibition assays.** AHL extracts
347 were tested using the *C. violaceum* CV026 biosensor strain using a well-diffusion assay (55).
348 *C. violaceum* CV026 was grown in LB for 16 h at 30°C supplemented with kanamycin (50
349 µg/ml). This overnight culture was incorporated into LB agar plates (1.2%) by dilution
350 (1:100). In addition, induction plates also contained kanamycin (50 µg/ml) and inhibition
351 plates both kanamycin and C10 AHL (50 nM) (17248, Sigma-Aldrich, Pool, UK). A well (6
352 mm) was made into the centre of each solidified agar plate. Test AHL extracts (or controls)
353 were then added to the well (adjusting with dH₂O according to the dry weight of PAO1
354 culture used). The plates were then incubated at 30°C for 48 h. Distances of violaceum

355 induction or inhibition as determined by the extent of purple colouration or zone of
356 clearing, respectively, were then measured (mm).

357 **Cell-free culture supernatant.** Cultures of *P. aeruginosa* PAO1 were grown for 12, 18,
358 24 and 30 h and prepared as described previously for growth curves. MH broth was selected
359 as nutrient-limited media have been shown to enhance AHL production (9). Cells were
360 harvested (3900 *g*, 20 min, 4°C) and washed three times with ice cold 0.9% NaCl and dried
361 at 80°C for 24 h. In each case, differences in culture biomass (at OligoG CF-5/20
362 concentrations >2%) from cell-free culture supernatants, used for the screening of AHLs and
363 the extraction of all the virulence factors was corrected by normalisation according to dry
364 weight.

365 **Quantitation of extracellular virulence factors.** Pyocyanin was extracted from the
366 culture supernatant (700 µl) using chloroform in the ratio of 3:2 and re-extracted with 150
367 µl of 0.2 M HCl and the absorbance read at 520 nm (17). Rhamnolipids were extracted from
368 culture supernatant with ethyl acetate in a 1:1 ratio, vortexed for 15 sec and centrifuged
369 (10,000 *g*, 4°C, 5 min). The upper layer was removed and ethyl acetate extraction repeated
370 (x3) for each sample. The combined upper layer was left to evaporate overnight. Then 900
371 µl of orcinol reagent (0.19% orcinol in 53% H₂SO₄) was added to the precipitate, and
372 incubated at 80°C for 30 min, before reading the absorbance at 420 nm (51). Protease
373 activity was determined using 2% azocasein solution prepared in 50 mM phosphate buffer
374 saline (PBS), pH 7. The substrate and culture supernatant were incubated at 37°C in 1:1
375 ratio for 1 h in a reaction volume of 400 µl. The reaction was stopped by the addition of 500
376 µl of 10% trichloroacetic acid and centrifuged at 8000 *g* for 5 min to remove residual
377 azocasein. The absorbance was read at 400 nm (17). Elastase extraction employed, 200 µl
378 elastin Congo red solution (5 mg/ml in 0.1 M Tris-HCl pH 8; 1 mM CaCl₂) which was

379 incubated with 600 μ l of cell-free, culture supernatant at 37°C for 3 h at 200 rpm. The
380 mixture was then centrifuged at 3000 g for 10 min and the absorbance read at 490 nm (17).

381 **High performance liquid chromatography triple quadrupole mass spectrometry**
382 **(LC/MS).** AHLs were extracted as described above and freeze-dried until required. Freeze
383 dried samples were reconstituted in 200 μ l of acetonitrile (ACN) with 0.1% acetic acid and
384 7.2 ng/ml of the internal standard umbelliferone. Samples were vortexed, centrifuged (16),
385 (100 g, 4°C, 10 min) and supernatants filtered through 0.4 μ m syringe filter (Phenomenex,
386 UK) this was performed twice to increase metabolite extraction. Samples were kept on ice
387 throughout the extraction procedure prior to being run on the liquid chromatography Triple
388 quadrupole mass spectrometer (LC-QQQ-MS). Samples (5 μ l) were loaded onto a C18 XDB
389 Eclipse (1.8 μ m, 4.6 x 50 mm) reverse phase column (Agilent Technologies, Palo Alto, USA).
390 Samples were quantified using a 1200 series HPLC (Agilent Technologies, USA) coupled to a
391 6410B enhanced sensitivity triple quadruple (QQQ) mass spectrometer (Agilent
392 Technologies, USA). For detection using positive ion mode, mobile phase A comprised of 5
393 mM ammonium acetate in water modified with 0.1% acetic acid and B was acetonitrile
394 containing 0.1% acetic acid. The column was equilibrated in 2% B, before increasing in a
395 linear fashion to 100% over 6 min; with 100% B being maintained for a further 2 min before
396 column re-equilibration. The column temperature was maintained at 35°C for the duration
397 with a flow rate of 0.3 mL/min. Source parameters were as follows: temperature, 350 °C,
398 gas flow, 10 L/min; nebuliser, 35 psi; and capillary voltage, 4 kV. Data were analysed using
399 Agilent MassHunter QQQ Quantitative Analysis software (Version B.07.00). Peak areas were
400 normalized to the internal standard umbelliferone and concentrations calculated using
401 standard concentration curves, offset against blank values (the average peak areas for the
402 blanks).

403 **RNA extraction for real time PCR (qPCR).** RNA was extracted from 24 h cultures of *P.*
404 *aeruginosa* PAO1 grown at 37°C in MH broth +/- OligoG CF-5/20 (0.2, 2 and 10%). Cultures
405 were harvested (2000 *g*, 10 min), resuspended and adjusted to 1.0 x 10⁸ CFU/ml in PBS and
406 centrifuged (12,000 *g*, 2 min) and re-suspended in 0.5 ml RNA later and stored at -20°C until
407 required. Cells were pelleted (12,000 *g*, 2 min) and re-suspended with lysis buffer (RLT
408 buffer, QIAgen, Crawley, UK) containing 1% (v/v) β-mercaptoethanol. Cell debris was
409 pelleted via centrifugation (12,000 *g*, 2 min), resulting supernatants were removed into
410 fresh tubes, phenol:chloroform:isoamyl alcohol (25:24:1) was used to acquire total nucleic
411 acid. Total RNA was recovered after DNase I treatment using the RNeasy® Mini Kit
412 (QIAGEN) according to the manufacturer's instructions. Gel electrophoresis was used to
413 check the purity and integrity of the total RNA and RNA concentration was measured
414 spectrophotometrically and an additional purity check using the absorbance ratio of
415 260/280 nm (NanoVue, GE Healthcare, Little Chalfont, UK) and standardised to 300 ng/ml.
416 Reverse transcription reactions for cDNA synthesis included total RNA (300 ng) template, 1
417 µl of 50 µg/ml random primer and molecular grade water was added to give a final reaction
418 volume of 10 µl. RT-qPCR was performed in triplicate using NanoScript2 RT-Kit (primer
419 design, UK) and a final annealing step of 5 min at 65°C, after which point the samples were
420 cooled on ice. Annealed samples were then added to the extension mix; 4 µl of 4 x
421 nanoScript2 Buffer, 1 µl dNTP mix (10 mM), NanoScript2 enzyme at 1.5 µl (Primer Design,
422 Southampton, UK), and 2.5 µl molecular grade water and a final volume of 20 µl was
423 incubated at 25°C for 5 min and then at 42°C for 20 min.

424 **Real-time PCR (qPCR) for analysis of gene expression.** RT-qPCR for analysis of the
425 expression of QS genes was carried out using the primers presented in Table 1. Primer
426 specificity was tested on genomic DNA. RT-qPCR was performed in triplicate with three

427 replicate samples, using an ABI 7000 instrument (Life Technologies, UK). Each reaction
428 contained 2 μ l cDNA, 12.5 μ l (x2) of SYBR-Green PCR master mix (PrecisionPlus Mastermix;
429 Primer Design, Southampton, UK), 10 mM of each primer and made up to 25 μ l with highly
430 purified water (Qiagen). The thermal cycler profile comprised of initial denaturation at 95°C
431 for 2 min, 40 cycles of denaturation at 95°C for 15 sec, primer annealing at 58°C (15 s), and
432 extension at 72°C (30 s). A final extension at 72°C for 2 min was performed, followed by
433 cooling at 4°C. A dissociation step at 60°C was used to generate a melting curve for
434 verification of the amplified product. After RT-qPCR, the threshold was adjusted according
435 to the amplification curves of all evaluated genes. Comparison between groups was made
436 based on the cycle number at which both the target and the average of endogenous control
437 genes (*rpsL* and *proD*) attained threshold cycle (Ct) fluorescence. Analysis of relative gene
438 expression was achieved according to the $\Delta\Delta$ CT method (56).

439 **eDNA determination of *Pseudomonas aeruginosa* PAO1 biofilms treated with OligoG**
440 **CF-5/20 using a nucleic-acid specific cell impermeable fluorescent TOTO-1® stain.** The
441 effect of OligoG on formation of 24 h *P. aeruginosa* PAO1 biofilms was tested. For this,
442 adjusted *P. aeruginosa* PAO1 cultures (10^7 CFU/ml) were diluted (1:0) in MH broth +/-OligoG
443 CF-5/20 (0.5, 2, 6% w/v) and then incubated in Whatman 96-well glass-bottomed plates at
444 37°C for 24 h with gentle agitation prior to staining. The effect of OligoG on established 24 h
445 biofilms was also tested to look at its effect on biofilm disruption. For this, biofilms were
446 grown without OligoG treatment using adjusted *P. aeruginosa* PAO1 cultures (10^7 CFU/ml),
447 diluted (1:0) in MH broth. After 24 h incubation, half the supernatant was removed and
448 replaced with 100 μ l fresh MH broth \pm OligoG CF-5/20 (0.5, 2, 6% w/v) and the samples
449 incubated for a further 24 h before staining. After OligoG treatment, the supernatant was

450 removed and biofilms stained with TOTO[®]-1 (Thermofisher) for 25 mins. Biofilm samples
451 were imaged using a Leica TCS SP5 confocal system with a x63 lens.

452 For fluorescence determination of eDNA, biofilms were homogenised by vigorous
453 pipetting and the resulting supernatant filtered (0.2 µm). Culture purity was confirmed by
454 plating a loopful of supernatant onto non-selective blood agar. Supernatants were stained
455 with TOTO[®]-1 at room temperature for 35 min and fluorescence excitation/emission
456 measured at ~514/533 nm on a FLUOstar Optima plate reader (BMG LABTECH) (47).

457 **Synthesis of N-decanoyl cyclopentylamide (C10-CPA).** Decanoyl chloride (1 mol eq;
458 0.544 ml; 0.500 g; 2.6 mmol) was added dropwise to a stirring solution of cyclopentylamine
459 (2 mol eq; 0.513 ml; 0.443 g; 5.2 mmol) in anhydrous dichloromethane (5 ml) under
460 nitrogen atmosphere. The reaction was stirred for 6 h and then the solvent evaporated
461 under reduced pressure. The residue was re-dissolved in 20 ml of diethyl ether and washed
462 with water, 5% NaHCO₃, 0.2 M HCl and saturated NaCl solution. The organic layer was dried
463 over MgSO₄ and concentrated to furnish the N-cyclopentyldecanamide as a white solid and
464 confirmed by hydrogen-1 nuclear magnetic resonance (H-NMR), carbon-13 NMR and
465 electrospray ionization MS (30).

466 **Confocal laser scanning microscopy imaging of *Pseudomonas aeruginosa* biofilms**
467 **treated with QS inhibitors.** Overnight cultures of *P. aeruginosa* PAO1 grown in tryptone
468 soya broth (TSB) were adjusted to 10⁷ CFU/ml and 10 µl of adjusted cultures added to 90 µl
469 of MH broth in glass-bottomed 96 well plates. Biofilms of *P. aeruginosa* PAO1 were grown
470 (24 h) whilst being treated (rocking gently) with known AHL quorum sensing inhibitors of
471 2(5H)-Furanone, (283754, Sigma-Aldrich, Pool, UK) at (1.25 µg ml⁻¹ and 2.5 µg ml⁻¹ (14.9 and
472 29.7 µM respectively) (29, 30) and N-decanoyl cyclopentylamide (C10-CPA) at 100 and 250
473 µM (30). Untreated and OligoG-treated biofilms were used as controls. Planktonic

474 cells/supernatant was removed before staining the biofilms with 6 % LIVE/DEAD[®] BacLight™
475 bacterial viability kit (Invitrogen, Paisley, UK) in PBS, incubating in the dark (10 min) and
476 imaging with a Leica TCS SP5 confocal system using a x 63 lens.

477 **Circular dichroism (CD) spectroscopy.** To evaluate whether AHLs influence the
478 conformation of OligoG CF-5/20, CD spectra were recorded on an Aviv 215 instrument (Aviv
479 Biomedical Inc., Lakewood, NJ) from 260 to 200 nm, 1 nm band-width, using a 0.5-cm quartz
480 cell at 37°C. OligoG CF-5/20 was dissolved in 100 mM NaCl, 10 mM Tris-HCl, pH 7.5, at a
481 concentration of 0.5 mg/ml and either C4-AHL or 3-oxo-C12-AHL (Sigma-Aldrich, Pool, UK,
482 09014 and 09945) was added stepwise from 1mg/ml stock solutions. Buffer baselines and
483 the intrinsic AHL spectra were subtracted, and spectra were corrected for dilution. Data are
484 presented as mean-residue-weight ellipticities $[\Theta]_{MRW}$ assuming $M_r = 194$ g/mol for the
485 OligoG CF-5/20 monosaccharides.

486 **Statistical analysis.** Microsoft Excel was used to perform statistical analysis including
487 one-way ANOVA using the Tukey-Kramer post-test and the minimum significant difference
488 (MSD) was calculated using the Tukey-Kramer method (57). $P < 0.05$ was considered
489 significant.

490

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500

501 REFERENCES

502 1. Rada B, Leto TL. 2013. Pyocyanin effects on respiratory epithelium: relevance in
503 *Pseudomonas aeruginosa* airway infections. Trends Microbiol 21:73-81.

504 2. Silby MW, Winstanley C, Godfrey SA, Levy SB, Jackson RW. 2011. *Pseudomonas*
505 genomes: diverse and adaptable. FEMS Microbiol Rev 35:652-680.

506 3. Mathee K, Narasimhan G, Valdes C, Qiu X, Matewish JM, Koehrsen M, Rokas A, Yandava
507 CN, Engels R, Zeng E, Olavarietta R, Doud M, Smith RS, Montgomery P, White JR,
508 Godfrey PA, Kodira C, Birren B, Galagan JE, Lory S. 2008. Dynamics of *Pseudomonas*
509 *aeruginosa* genome evolution. Proc Natl Acad Sci USA 105:3100-3105.

510 4. Khan S, Tondervik A, Sletta H; Klinkenberg G, Emanuel C, Onsøyen E, Myrvold R, Howe
511 RA, Walsh TR, Hill KE, Thomas DW. 2012. Overcoming drug resistance with alginate
512 oligosaccharides able to potentiate the action of selected antibiotics. Antimicrob Agents
513 Chemother 56:5134-5141.

514 5. Powell LC, Sowedan A, Khan S, Wright CJ, Hawkins K, Onsøyen E, Myrvold R, Hill KE,
515 Thomas DW. 2013. The effect of alginate oligosaccharides on the mechanical
516 properties of Gram-negative biofilms. Biofouling 29:413-421.

517 6. Roberts JL, Khan S, Emanuel C, Powell LC, Pritchard MF, Onsøyen E, Myrvold R, Thomas
518 DW, Hill KE. 2013. An in vitro study of alginate oligomer therapies on oral biofilms. J
519 Dent 41:892-899.

520 7. Powell LC, Pritchard MF, Emanuel C, Onsøyen E, Rye PD, Wright CJ, Hill KE, Thomas DW.
521 A nanoscale characterization of the interaction of a novel alginate oligomer with the cell

- 522 surface and motility of *Pseudomonas aeruginosa*. 2014. *Am J Respir Cell Mol Biol*
523 50:483-492.
- 524 8. Tøndervik A, Sletta H, Klinkenberg G, Emanuel C, Powell LC, Pritchard MF, Khan S,
525 Craine KM, Onsjøen E, Rye PD, Wright C, Thomas DW, Hill KE. 2014. Alginate
526 oligosaccharides inhibit fungal cell growth and potentiate the activity of antifungals
527 against *Candida* and *Aspergillus* spp. *PLoS One* 9:e112518.
- 528 9. Duan K, Surette MG. 2007. Environmental regulation of *Pseudomonas aeruginosa* PAO1
529 Las and Rhl quorum-sensing systems. *J Bacteriol* 189:4827-4836.
- 530 10. Fuqua WC, Winans SC. 1994. A LuxR-LuxI type regulatory system activates
531 *Agrobacterium* Ti plasmid conjugal transfer in the presence of a plant tumor metabolite.
532 *J Bacteriol* 176:2796-2806.
- 533 11. Ng WL, Bassler BL. 2009. Bacterial quorum-sensing network architectures. *Annu Rev*
534 *Genet* 43:197-222.
- 535 12. Schuster M, Lostroh CP, Ogi T, Greenberg EP. 2003. Identification, timing, and signal
536 specificity of *Pseudomonas aeruginosa* quorum-controlled genes: a transcriptome
537 analysis. *J Bacteriol* 185:2066-79.
- 538 13. Lee J, Zhang L. 2015. The hierarchy quorum sensing network in *Pseudomonas*
539 *aeruginosa*. *Protein Cell* 6:26-41.
- 540 14. Lee J, Wu J, Deng Y, Wang J, Wang C, Wang J, Chang C, Dong Y, Williams P, Zhang, L-H.
541 2013. A cell-cell communication signal integrates quorum sensing and stress response.
542 *Nat Chem Biol* 9:339-343.
- 543 15. Wagner VE, Bushnell D, Passador L, Brooks AI, Iglewski BH. 2003. Microarray analysis of
544 *Pseudomonas aeruginosa* quorum-sensing regulons: effects of growth phase and
545 environment. *J Bacteriol* 185:2080-2095.

- 546 16. Williams P, Camara M. 2009. Quorum sensing and environmental adaptation in
547 *Pseudomonas aeruginosa*: a tale of regulatory networks and multifunctional signal
548 molecules. *Curr Opin Microbiol* 12:182-191.
- 549 17. Sarabhai S, Sharma P, Capalash N. 2013. Ellagic acid derivatives from *Terminalia chebula*
550 Retz. downregulate the expression of quorum sensing genes to attenuate *Pseudomonas*
551 *aeruginosa* PAO1 virulence. *PLoS One* 8:e53441.
- 552 18. Caldwell CC, Chen Y, Goetzmann HS, Hao Y, Borchers MT, Hassett DJ, Young LR, Mavrodi
553 D, Thomashow L, Lau GW. 2009. *Pseudomonas aeruginosa* exotoxin pyocyanin causes
554 cystic fibrosis airway pathogenesis. *Am J Pathol* 175:2473-2488.
- 555 19. Lau GW, Ran H, Kong F, Hassett DJ, Mavrodi D. 2004. *Pseudomonas aeruginosa*
556 pyocyanin is critical for lung infection in mice. *Infect Immun* 72:4275-4278.
- 557 20. Barken KB, Pamp SJ, Yang L, Gjermansen M, Bertrand J, Klausen M, Givskov M,
558 Whitchurch C, Engel J, and Tolker-Nielsen T. 2008. Roles of type IV pili, flagellum-
559 mediated motility and extracellular DNA in the formation of mature multicellular
560 structures in *Pseudomonas aeruginosa* biofilms. *Environ Microbiol* 10:2331-2343.
- 561 21. Allesen-Holm M, Barken KB, Yang L, Klausen M, Webb JS, Kjelleberg S, Molin S, Givskov
562 M, Tolker-Nielsen T. 2006. A characterization of DNA release in *Pseudomonas*
563 *aeruginosa* cultures and biofilms. *Mol Microbiol* 59:1114-1128.
- 564 22. Zhang L, Gao Q, Chen W, Qin H, Hengzhuang W, Chen Y, Yang L, Zhang G. 2013.
565 Regulation of *pqs* quorum sensing via catabolite repression control in *Pseudomonas*
566 *aeruginosa*. *Microbiology* 159:1931-1936.
- 567 23. Dekimpe V, Deziel E. 2009. Revisiting the quorum-sensing hierarchy in *Pseudomonas*
568 *aeruginosa*: the transcriptional regulator RhIR regulates LasR-specific factors.
569 *Microbiology* 155:712-723.

- 570 24. Juhas M, Eberl L, Tummler B. 2005. Quorum sensing: the power of cooperation in the
571 world of *Pseudomonas*. *Environ Microbiol* 7:459-471.
- 572 25. Riedel K, Hentzer M, Geisenberger O, Huber B, Steidle A, Wu H, Høiby N, Givskov M,
573 Molin S, Eberl, L. 2001. N-Acylhomoserine-lactone-mediated communication between
574 *Pseudomonas aeruginosa* and *Burkholderia cepacia* in mixed biofilms. *Microbiology*
575 147:3249–3262.
- 576 26. Cooley M, Chhabra SR, Williams P. 2008. N-Acylhomoserine lactone-mediated quorum
577 sensing: a twist in the tail and a blow for host immunity. *Chem Biol* 15:1141-1147.
- 578 27. Jahoor A, Patel R, Bryan A, Do C, Krier J, Watters C, Wahli W, Li G, Williams, S C,
579 Rumbaugh K P. 2008. Peroxisome proliferator-activated receptors mediate host cell
580 proinflammatory responses to *Pseudomonas aeruginosa* autoinducer. *J Bacteriol*
581 190:4408-4415.
- 582 28. Stehling EG, daSilveira WD, Leite DS. 2008. Study of biological characteristics of
583 *Pseudomonas aeruginosa* strains isolated from patients with cystic fibrosis and from
584 patients with extra-pulmonary infections. *Braz J Infect Dis* 12:86-88.
- 585 29. Ponnusamy K, Paul D, Kim YS, Kweon JH. 2010. 2(5H)-Furanone: A prospective strategy
586 for biofouling-control in membrane biofilm bacteria by quorum sensing inhibition. *Braz J*
587 *Microbiol* 41:227-234.
- 588 30. Ishida T, Ikeda T, Takiguchi N, Kuroda A, Ohtake H, Kato J. 2007. Inhibition of quorum
589 sensing in *Pseudomonas aeruginosa* by N-acyl cyclopentylamides. *Appl Environ*
590 *Microbiol* 73:3183-3188.
- 591 31. Donati I, Gamini A, Skjak-Braek G, Vetere A, Campa C, Coslovi A, Paoletti S. 2003.
592 Determination of the diadic composition of alginate by means of circular dichroism: a
593 fast and accurate improved method. *Carbohydr Res* 338:1139-1142.

- 594 32. Morris ER, Rees DA, Sanderson GR, Thom D. 1975. Conformation and circular dichroism
595 of uronic acid residues in glycosides and polysaccharides. *J Chem Soc-Perkin Trans 2*
596 13:1418-1425.
- 597 33. Yates EA, Philipp B, Buckley C, Atkinson S, Chhabra SR, Sockett RE, Goldner M, Dessaux
598 Y, Camara M, Smith H, Williams P. 2002. N-Acylhomoserine lactones undergo
599 lactonolysis in a pH-, temperature-, and acyl chain length-dependent manner during
600 growth of *Yersinia pseudotuberculosis* and *Pseudomonas aeruginosa*. *Infect Immun*
601 70:5635-5646.
- 602 34. DeSoyza A, Hall AJ, Mahenthiralingam E, Drevinek P, Kaca W, Drulis-Kawa Z, Stoitsova S
603 R, Toth V, Coenye T, Zlosnik J E A, Burns J L, Sa' -Correia I, De Vos D, Pirnay J-P, Kidd T J,
604 Reid D, Manos J, Klockgether J, Wiehlmann L, Tummler B, McClean S, Winstanley C.
605 2013. Developing an international *Pseudomonas aeruginosa* reference panel.
606 *MicrobiologyOpen*. 2:1010-1023.
- 607 35. Smith EE, Buckley DG, Wu Z, Saenphimmachak C, Hoffman LR, D'Argenio DA, Miller S L,
608 Ramsey B W, Speert D P, Moskowitz S M, Burns J L, Kaul R, Olson M V. 2006. Genetic
609 adaptation by *Pseudomonas aeruginosa* to the airways of cystic fibrosis patients. *Proc*
610 *Natl Acad Sci U S A* 103:8487-8492.
- 611 36. Caiazza NC, Shanks RM, O'Toole GA. 2005. Rhamnolipids modulate swarming motility
612 patterns of *Pseudomonas aeruginosa*. *J Bacteriol* 187:7351-7361.
- 613 37. Overhage J, Lewenza S, Marr AK, Hancock RE. 2007. Identification of genes involved in
614 swarming motility using a *Pseudomonas aeruginosa* PAO1 mini-Tn5-lux mutant library. *J*
615 *Bacteriol* 189:2164-2169.

- 616 38. Lépine F, Déziel E, Milot S, Rahme LG. 2003. A stable isotope dilution assay for the
617 quantification of the *Pseudomonas* quinolone signal in *Pseudomonas aeruginosa*
618 cultures. *Biochim Biophys Acta* 1622:36-41.
- 619 39. Schuster M, Greenberg EP. 2006. A network of networks: quorum-sensing gene
620 regulation in *Pseudomonas aeruginosa*. *Int J Med Microbiol* 296:73-81.
- 621 40. Worthington RJ, Blackledge MS, Melander C. 2013. Small-molecule inhibition of
622 bacterial two-component systems to combat antibiotic resistance and virulence. *Future*
623 *Med Chem* 5:1265–1284.
- 624 41. Beier D, Gross R. 2006. Regulation of bacterial virulence by two-component systems.
625 *Curr Opin Microbiol* 9:143-52.
- 626 42. Balasubramanian D, Schneper L, Kumari H, Mathee K. 2013. A dynamic and intricate
627 regulatory network determines *Pseudomonas aeruginosa* virulence. *Nucleic Acids Res.*
628 41:1-20.
- 629 43. Cao Q, Wang Y, Chen F, Xia Y, Lou J, Zhang X, Yang N, Sun X, Zhang Q, Zhuo C, Huang X,
630 Deng X, Yang C-G, Ye Y, Zhao J, Wu M, Lan L. 2014. A novel signal transduction pathway
631 that modulates *rhl* quorum sensing and bacterial virulence in *Pseudomonas aeruginosa*.
632 *PLoS Pathog* 10:e1004340.
- 633 44. Son MS, Matthews WJ, Jr., Kang Y, Nguyen DT, Hoang TT. 2007. In vivo evidence of
634 *Pseudomonas aeruginosa* nutrient acquisition and pathogenesis in the lungs of cystic
635 fibrosis patients. *Infect Immun* 75:5313-5324.
- 636 45. Okkotsu Y, Tiekou P, Fitzsimmons LF, Churchill ME, Schurr MJ. 2013. *Pseudomonas*
637 *aeruginosa* AlgR phosphorylation modulates rhamnolipid production and motility. *J*
638 *Bacteriol* 195:5499–5515.

- 639 46. Wei Q, Ma LZ. 2013. Biofilm matrix and its regulation in *Pseudomonas aeruginosa*. Int J
640 Mol Sci 14:20983-21005.
- 641 47. Das T, Manefield M. 2012. Pyocyanin promotes extracellular DNA release in
642 *Pseudomonas aeruginosa* PLoS One 7: e46718.
- 643 48. Ruer S, Pinotsis N, Steadman D, Waksman G, Remaut H. 2015. Virulence-targeted
644 antibacterials: concept, promise, and susceptibility to resistance mechanisms. Chem
645 Biol Drug Des86:379-399.
- 646 49. Maeda T, Garcia-Contreras R, Pu M, Sheng L, Garcia LR, Tomas M, Wood T K. 2012.
647 Quorum quenching quandary: resistance to antivirulence compounds. ISME J 6:493-
648 501.
- 649 50. Janssens JC, De Keersmaecker SC, De Vos DE, Vanderleyden J. 2008. Small molecules for
650 interference with cell-cell-communication systems in Gram-negative bacteria. Curr Med
651 Chem 15:2144–2156.
- 652 51. Welsh MA, Eibergen NR, Moore JD, Blackwell HE. 2015. Small molecule disruption of
653 quorum sensing cross-regulation in *Pseudomonas aeruginosa* causes major and
654 unexpected alterations to virulence phenotypes. J Am Chem Soc 137:1510-1519.
- 655 52. Moore JD, Rossi FM, Welsh MA, Nyffeler KE, Blackwell HE. 2015. A Comparative analysis
656 of synthetic quorum sensing modulators in *Pseudomonas aeruginosa*: new insights into
657 mechanism, active efflux susceptibility, phenotypic response, and next-generation
658 ligand design. J Am Chem Soc 137:14626-14639.
- 659 53. Hentzer M, Wu H, Andersen JB, Riedel K, Rasmussen TB, Bagge N, Kumar N, Schembri M
660 A, Song Z, Kristoffersen P, Manefield M, Costerton J W, Mølin S, Eberl L, Steinberg P,
661 Kjelleberg S, Høiby N, Givskov M. 2003. Attenuation of *Pseudomonas aeruginosa*
662 virulence by quorum sensing inhibitors. EMBO J 22:3803-3815.

- 663 54. Smyth TJP, Perfumo A, Marchant R, Banat IM. 2010. Isolation and analysis of low
664 molecular weight microbial glycolipids, p 3705-3723. *In* Timmis KN (ed) Handbook of
665 hydrocarbon and lipid microbiology. Springer:Berlin Heidelberg.
- 666 55. Ravn L, Christensen AB, Molin S, Givskov M, Gram L. 2001. Methods for detecting
667 acylated homoserine lactones produced by Gram negative bacteria and their
668 application in studies of AHL-production kinetics. *J Microbiol Methods* 44:239-251.
- 669 56. Bustin SA, Benes V, Garson JA, Hellemans J, Huggett J, Kubista M, Mueller R, Nolan T,
670 Pfaffl M W, Shipley G L, Vandesompele, J, Wittwer C T. 2009. The MIQE guidelines:
671 minimum information for publication of quantitative real-time PCR experiments. *Clin*
672 *Chem* 55:611-622.
- 673 57. Fry JC. 1997. One-way analysis of variance, p 3-39. *In* Fry JC (ed) *Biological data*
674 *analysis: a practical approach*. Oxford University Press: Oxford.
- 675 58. Wang E W, Jung J Y, Pashia M E, Nason R, Scholnick S, Chole R A. 2005. Otopathogenic
676 *Pseudomonas aeruginosa* strains as competent biofilm formers. *Arch Otolaryngol Head*
677 *Neck Surg* 131:983-989.
- 678 59. Wang L, Zhang C, Gong F, Li H, Xie X, Xia C, Chen J, Song Y, Shen A, Song J. 2011.
679 Influence of *Pseudomonas aeruginosa pvdQ* gene on altering antibiotic susceptibility
680 under swarming conditions. *Curr Microbiol* 63:377-386.
- 681 60. Savli H, Karadenizli A, Kolayli F, Gundes S, Ozbek U, Vahaboglu H. 2003. Expression
682 stability of six housekeeping genes: a proposal for resistance gene quantification studies
683 of *Pseudomonas aeruginosa* by real-time quantitative RT-PCR. *J Med Microbiol* 52:403-
684 408.

Table 1. Genes and primers used for qPCR in this study.

Gene	Forward Primer (5' - 3')	Reverse Primer (5' - 3')	Forward primer			Reverse primer			Product size (bp)	Reference
			BP	GC	TM	BP	GC	TM		
<i>lasI</i>	TGTTCAAGGAGCGCAAAGG	ATGGCGAAACGGCTGAGTT	19	52.6	62.4	19	52.6	63	244	58
<i>lasR</i>	AGCGACCTTGGATTCTCGAAG	CGAAGAACTCGTGCTGCTTTC	21	52.4	63	21	52.4	62.5	226	58
<i>rhII</i>	TGCTCTCTGAATCGCTGGAA	GTTTGC GGATGGTCGAACTG	20	50	59.1	20	55	59.83	154	58
<i>rhIR</i>	TTGCTGAGCGTGCTTTCC	AGGATGATGGCGATTTCCC	19	52.6	62.6	19	52.6	62.1	228	58
* <i>rpsL</i>	CCTCGTACATCGGTGGTGAAG	CCCTGCTTACGGTCTTTGACAC	21	57.1	62.8	22	54.5	63.1	148	59
* <i>proD</i>	GGGCGAAGAAGGAAATGGTC	CAGGTGGCGTAGGTAGAGAA	20	55	63.1	20	55	58	178	60

*Reference/endogenous control genes; BP, primer length (basepairs); GC, G-C content of primer; TM, melting temperature of primer

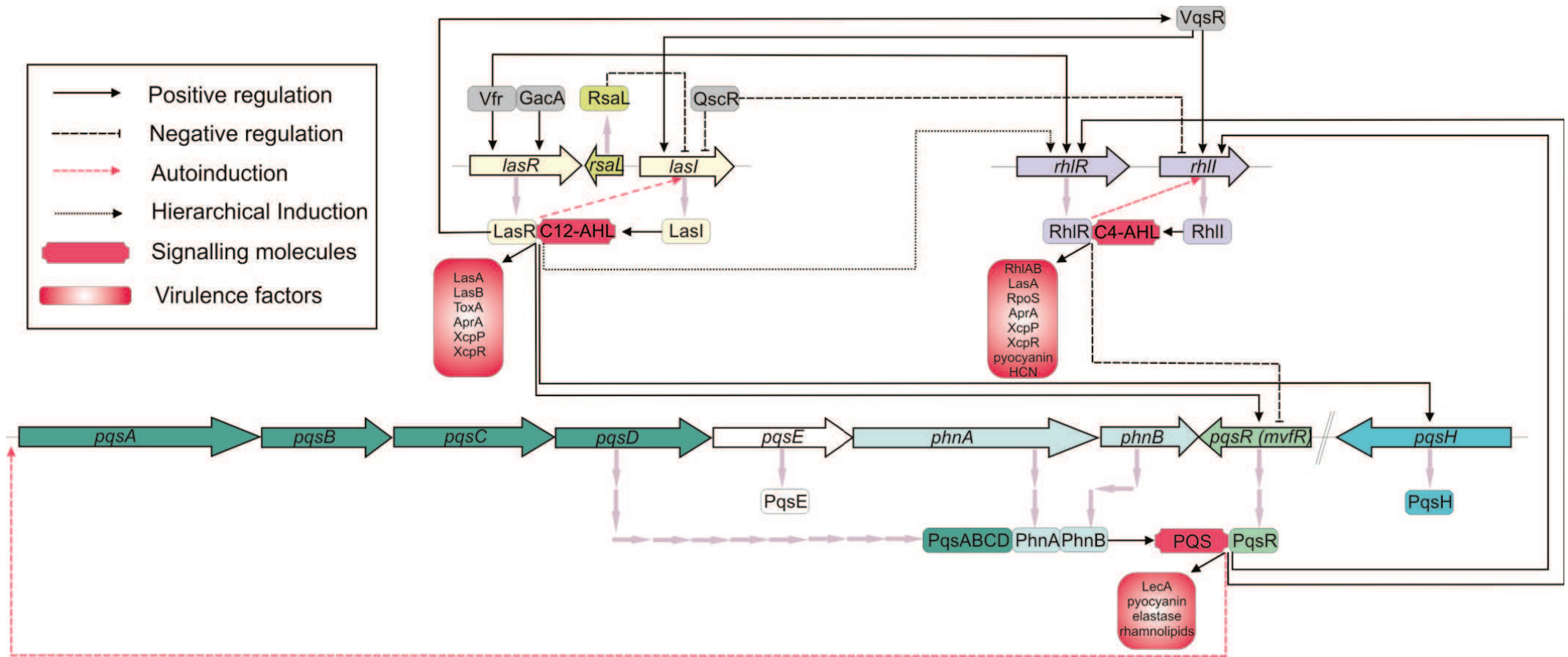


FIG 1 Schematic diagram of the *Pseudomonas aeruginosa* virulence regulatory network showing the three major QS signalling pathways namely, the acyl homoserine lactone Las and Rhl operons and the 2-heptyl-3-hydroxy-4-quinolone *Pseudomonas* quinolone signal (PQS) operon. Differences in culture biomass (at $\geq 2\%$ OligoG) were corrected according to dry weight.

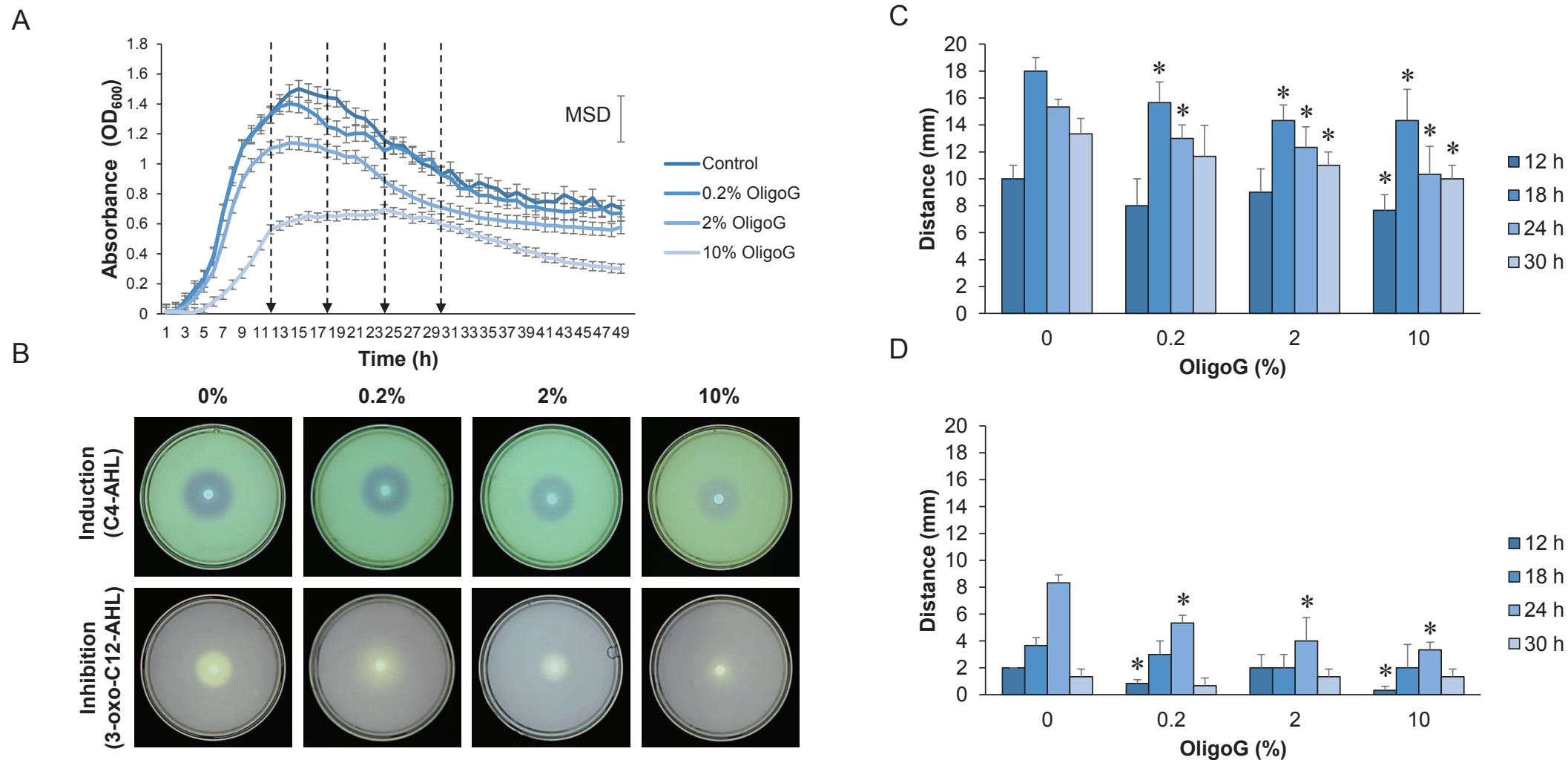
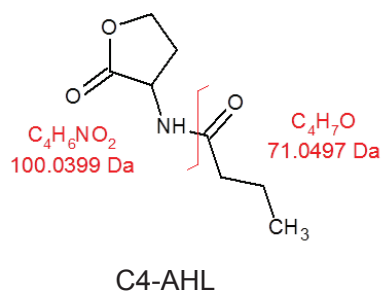
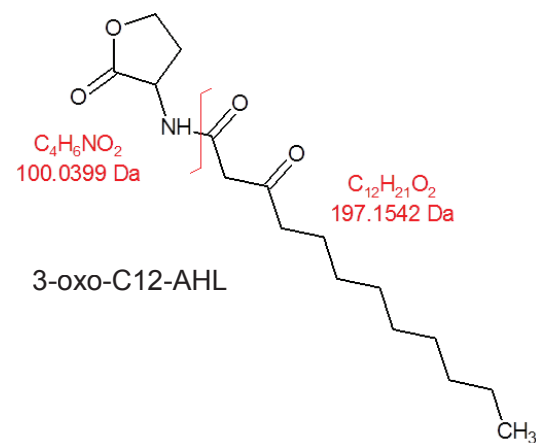


FIG 2 Effect of OligoG CF-5/20 on the growth of *P. aeruginosa* PAO1 and the production of signalling molecules using the biosensor *Chromobacterium violaceum* CV026. (A) Growth curves of *P. aeruginosa* PAO1 treated with OligoG CF-5/20 showing four specific sampling times (12, 18, 24 and 30 h) for AHL extractions (arrows). Well-diffusion time-course assay detecting AHLs from (B) 24 h or (C) and (D) 12, 18, 24 and 30 h extracts of *P. aeruginosa* cultures treated with OligoG (0.2, 2 and 10 %). (B) and (C) Induction (zone of colouration) or (B) and (D) Inhibition (zone of clearing) of violacein synthesis in *C. violaceum* CV026 showing changes in C4- and 3-oxo-C12-AHL production following OligoG treatment (n = 3 ± standard deviation; * P < 0.05). MSD, minimum significant difference. Differences in culture bio-mass (at ≥2% OligoG) were corrected according to dry weight.

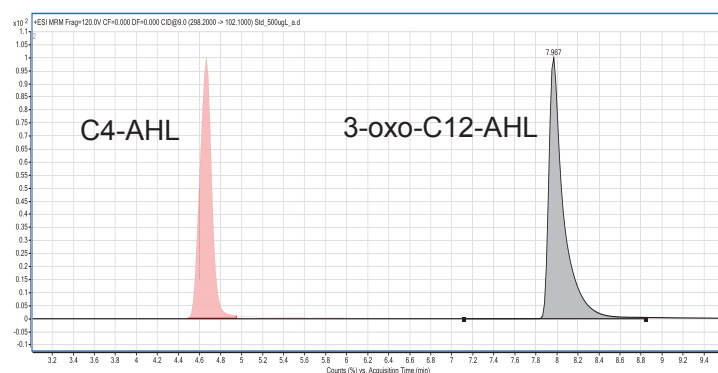
A



B



C



D

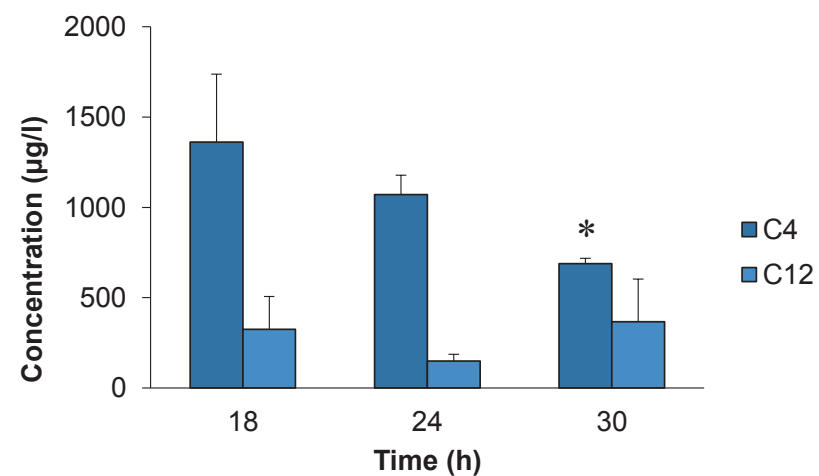
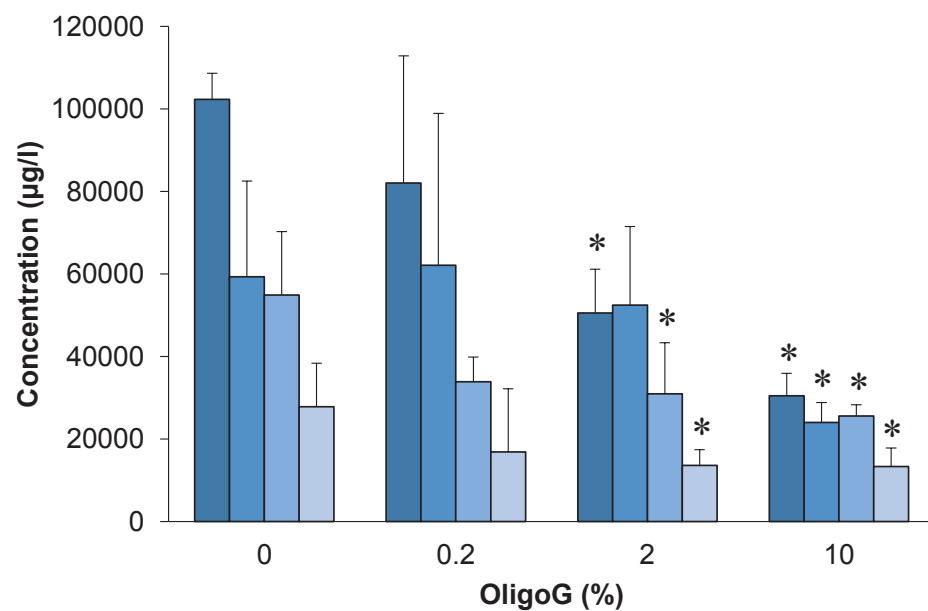


FIG 3 Method development for detection and quantification of acyl homoserone lactones (AHLs). (A) Structure of C4-AHL. (B) Structure of 3-oxo-C12-AHL. (C) C4-AHL and 3-oxo-C12-AHL LC/Mass spectrometry peaks. (D) Initial time course showing LC/MS quantification of AHL concentrations (µg/L) from *P. aeruginosa* PAO1 grown in Mueller Hinton (MH) broth at different time points (18, 24 and 30 h). (n = 3 ± standard deviation; * P<0.05). Differences in culture bio-mass (at ≥2% OligoG) were corrected according to dry weight.

A



B

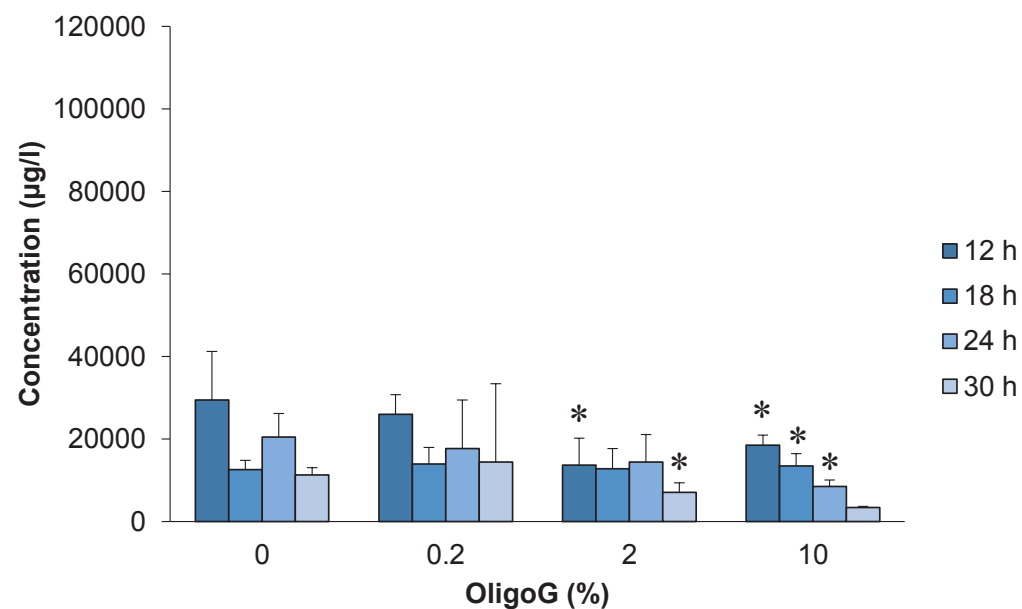


FIG 4 Effect of OligoG CF-5/20 on AHL concentrations ($\mu\text{g/L}$) determined by LC/MS at different time points (12, 18, 24 and 30 h) in *P. aeruginosa* PAO1 grown in Mueller Hinton (MH) broth \pm OligoG (0.2, 2 and 10%). A) C4-AHL. B) 3-oxo-C12-AHL. ($n = 3 \pm$ standard deviation; * $P < 0.05$). Differences in culture bio-mass (at $\geq 2\%$ OligoG) were corrected according to dry weight.

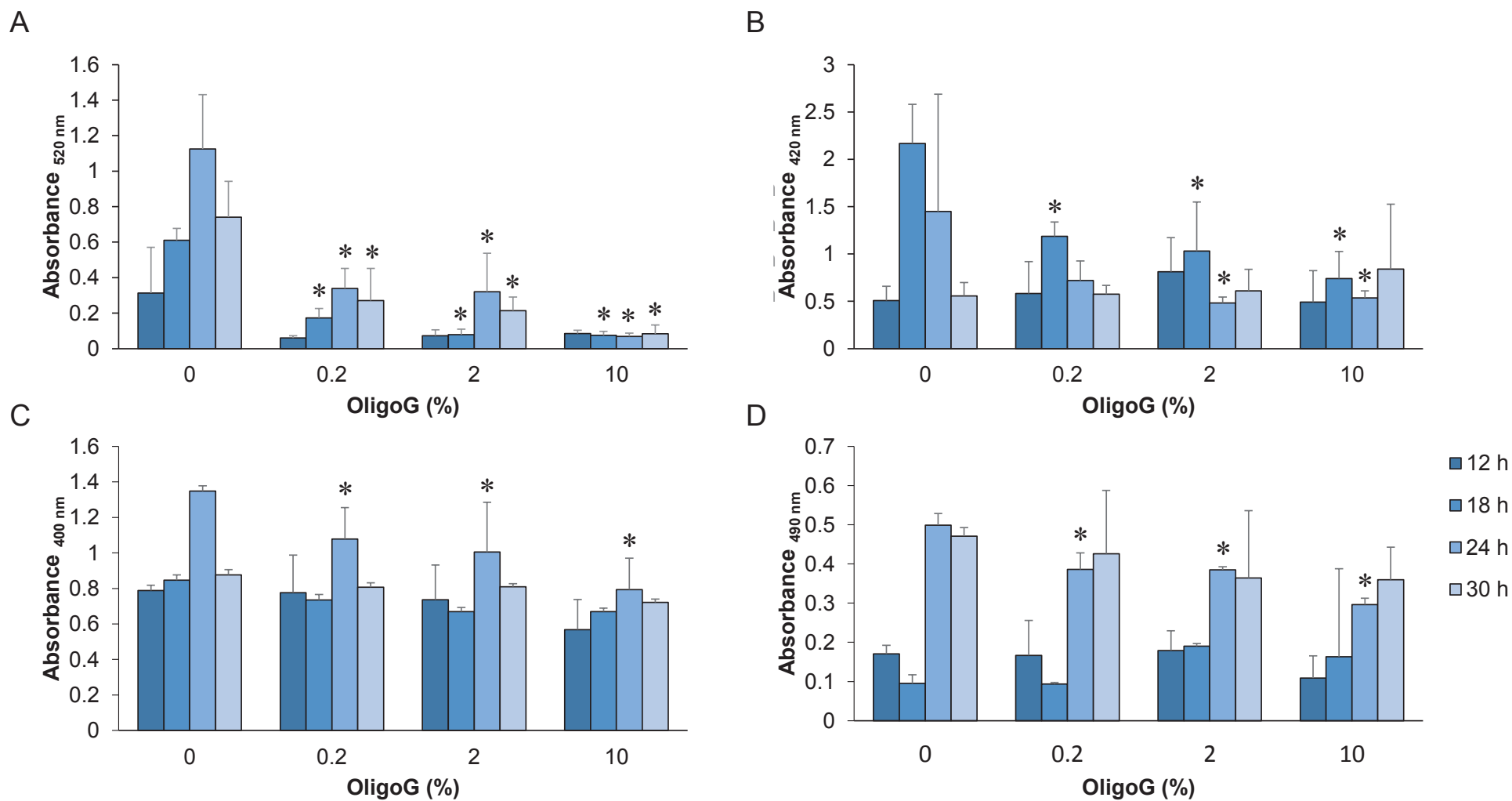


FIG 5 Extracellular virulence factor production by *P. aeruginosa* from 12, 18, 24 and 30 h cell free culture supernatants treated with OligoG CF-5/20 (0.2, 2 and 10 %). (A) pyocyanin. (B) rhamnolipids. (C) total protease. (D) elastase. (n = 4 ± standard deviation; * P<0.05). Differences in culture bio-mass (at ≥2% OligoG) were corrected according to dry weight.

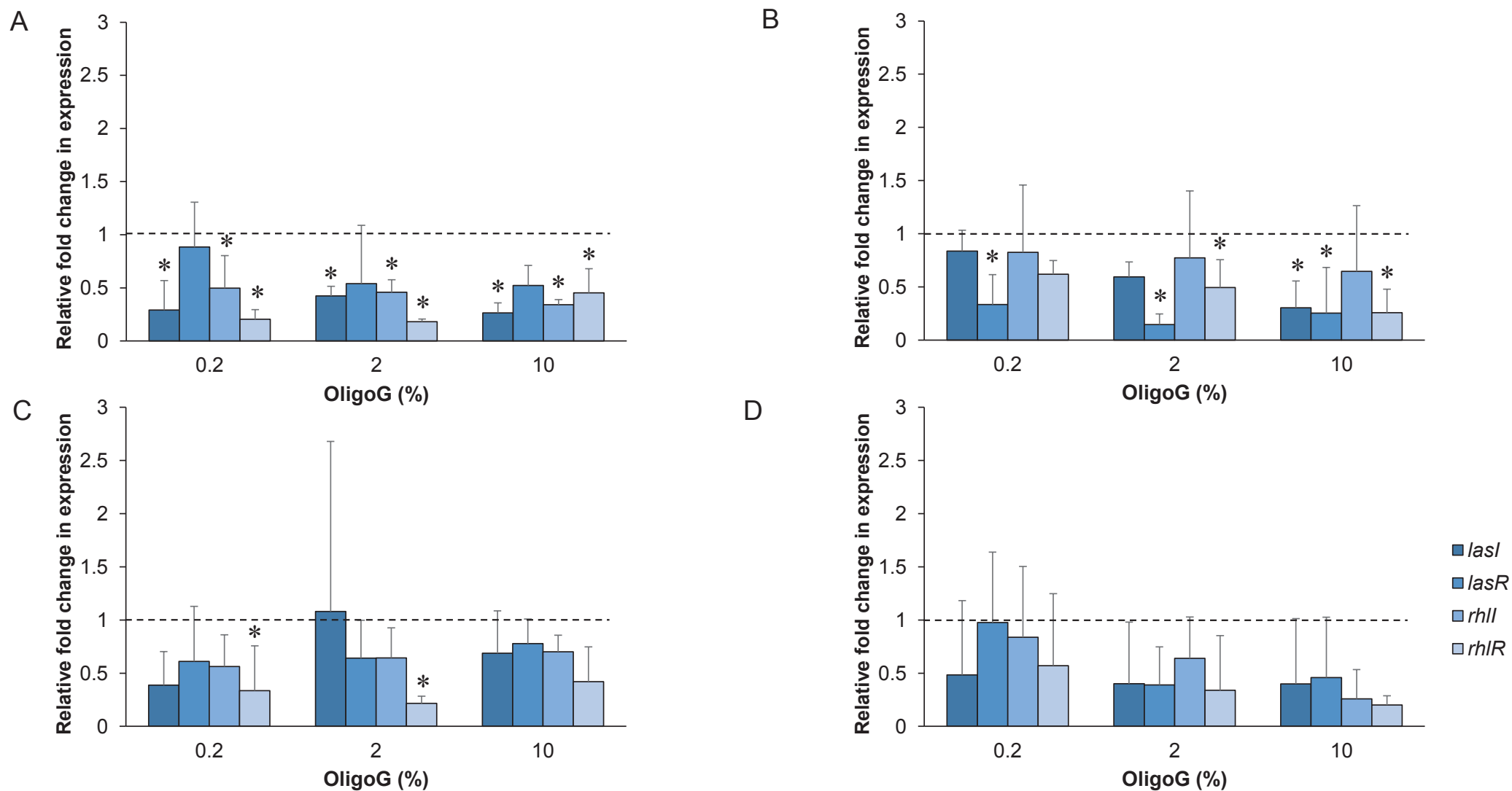
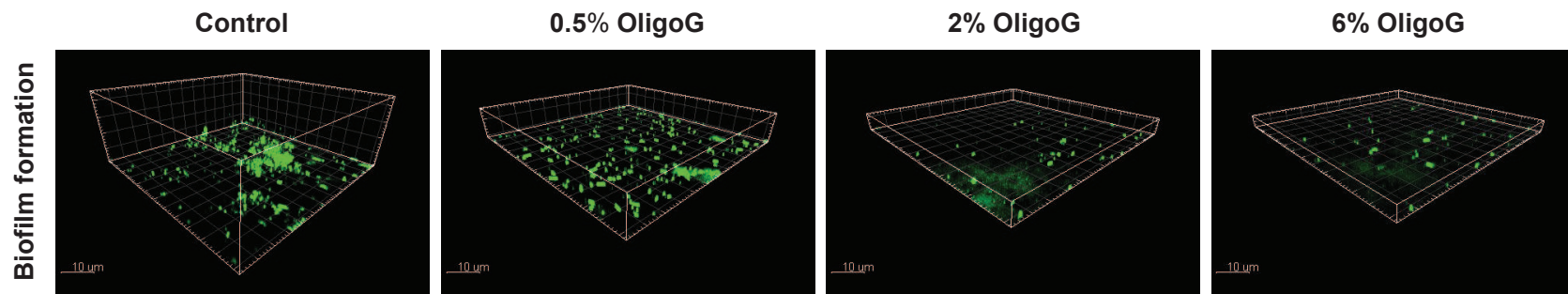
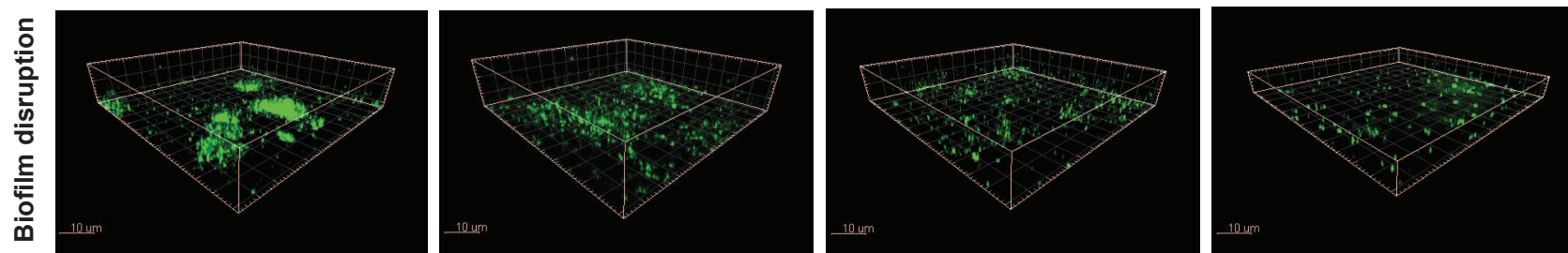


FIG 6 Relative fold change in gene expression compared to untreated control using quantitative PCR of *lasI/R*, *rhII/R* genes from 12, 18, 24 and 30 h cultures of *P. aeruginosa* PAO1 treated with OligoG CF-5/20 (0.2, 2 and 10%). (A) 12 h. (B) 18 h. (C) 24 h. (D) 30 h. (n = 3 ± standard deviation; * P<0.05). Differences in culture bio-mass (at ≥2% OligoG) were corrected according to dry weight.

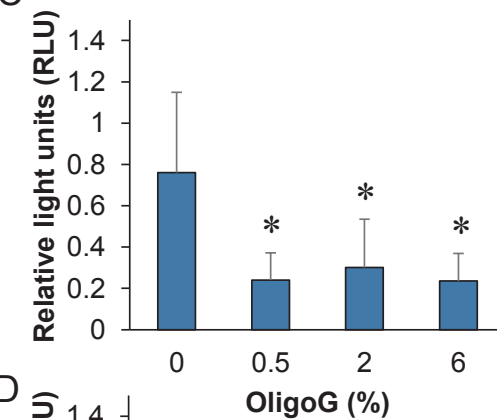
A



B



C



D

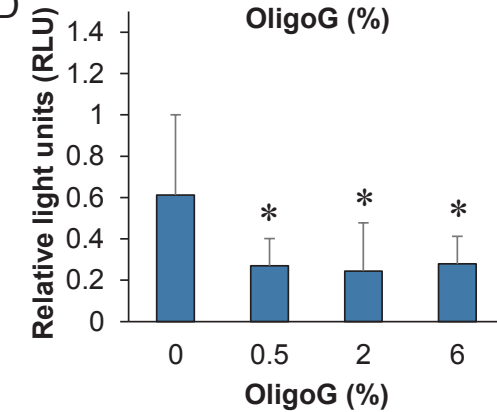


FIG 7 CLSM of *Pseudomonas aeruginosa* PAO1 biofilms treated with OligoG CF-5/20 (0.5, 2 and 10%) and stained with nucleic acid specific TOTO-1 (green). (A) Biofilm formation assay: Biofilms grown for 24 h in the presence of OligoG. (B) Biofilm disruption assay: 24 h established biofilms subsequently treated for 24 h with OligoG shown with corresponding fluorescence intensities in (C) and (D). (n = 3 ± standard deviation; * P<0.05).

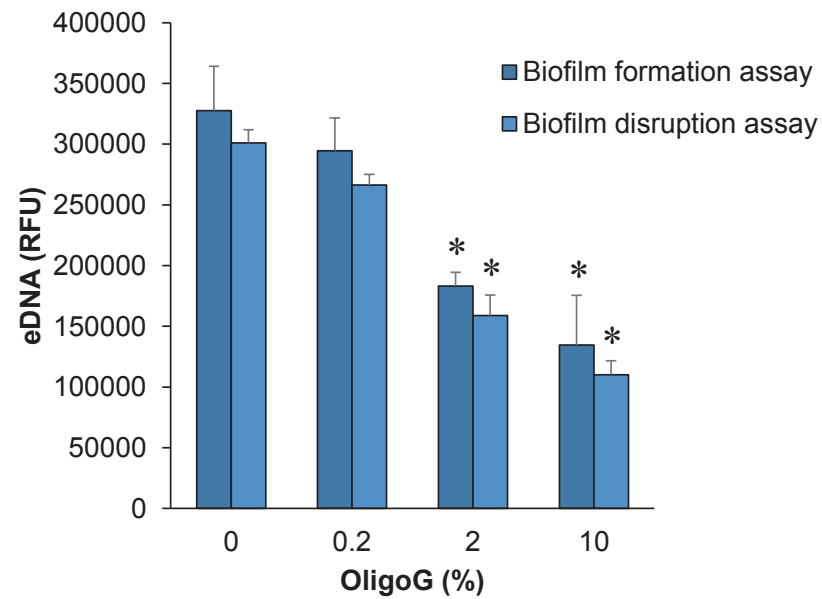


FIG 8 Determination of eDNA concentration. Effect of OligoG (0.2, 2 and 10 %) on relative eDNA concentration in *P. aeruginosa* biofilms. Biofilm formation assay: biofilms grown for 24 h in the presence of OligoG and Biofilm disruption assay: 24 h established biofilms subsequently treated for 24 h with OligoG. (n = 3 ± standard deviation; * P<0.05). Differences in culture bio-mass (at ≥2% OligoG) were corrected according to dry weight.

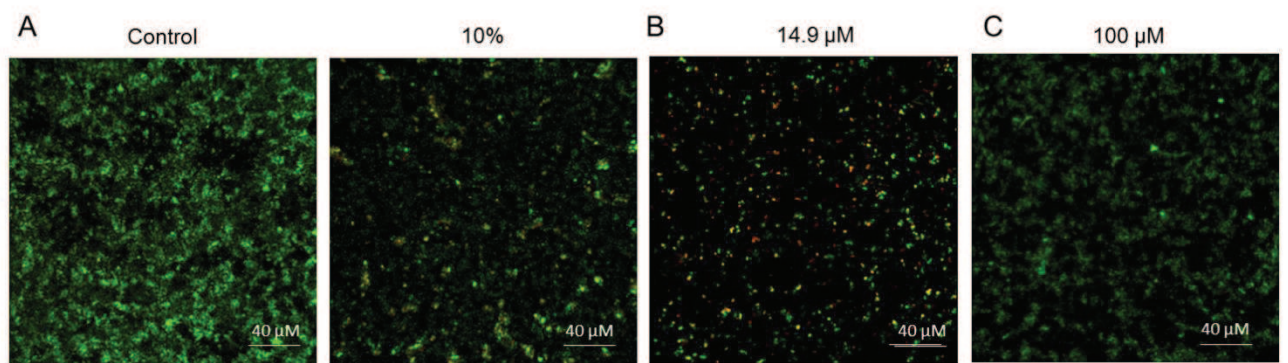


FIG S1 Confocal laser scanning microscopy of *Pseudomonas aeruginosa* PAO1 24 h biofilms treated with quorum sensing inhibitors. (A) OligoG CF-5/20, 0 and 10%. (B) 2(5H)-furanone, 1.25 μg/mL (14.9 μM). (C) N-decanoyl cyclopentylamide (C10-CPA), 100 μM, (n=3).

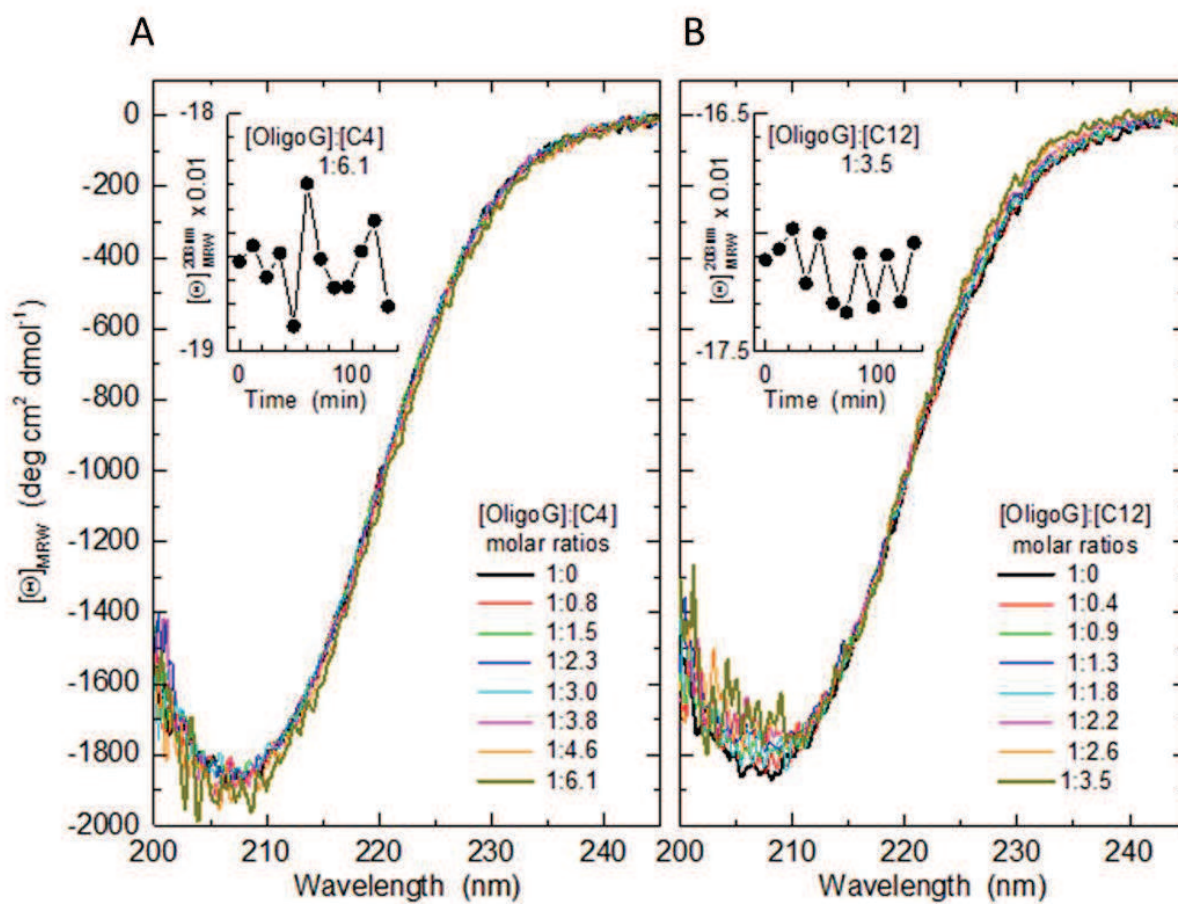


FIG S2 Circular dichroism spectra showing the effect of OligoG (at a range of molar ratios) on homoserine lactones. (A) C4-AHL and (B) 3-oxo-C12 AHL. Insets show a time course recorded at 208nm after addition of AHLs at their maximum concentration.