A *Streptococcus* Quorum Sensing System Enables Suppression of Innate Immunity

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**ABSTRACT** Some bacterial pathogens utilize cell-cell communication systems, such as quorum sensing (QS), to coordinate genetic programs during host colonization and infection. The human-restricted pathosymbiont *Streptococcus pyogenes* (group A streptococcus [GAS]) uses the Rgg2/Rgg3 QS system to modify the bacterial surface, enabling biofilm formation and lysozyme resistance. Here, we demonstrate that innate immune cell responses to GAS are substantially altered by the QS status of the bacteria. We found that macrophage activation, stimulated by multiple agonists and assessed by cytokine production and NF-κB activity, was substantially suppressed upon interaction with QS-active GAS but not QS-inactive bacteria. Neither macrophage viability nor bacterial adherence, internalization, or survival were altered by the QS activation status, yet tumor necrosis factor alpha (TNF-α), interleukin 6 (IL-6), and interferon beta (IFN-β) levels and NF-κB reporter activity were drastically lower following infection with QS-active GAS. Suppression required contact between viable bacteria and macrophages. A QS-regulated biosynthetic gene cluster (BGC) in the GAS genome, encoding several putative enzymes, was also required for macrophage modulation. Our findings suggest a model wherein upon contact with macrophages, QS-active GAS produce a BGC-derived factor capable of suppressing inflammatory responses. The suppressive capability of QS-active GAS is abolished after treatment with a specific QS inhibitor. These observations suggest that interfering with the ability of bacteria to collaborate via QS can serve as a strategy to counteract microbial efforts to manipulate host defenses.

**IMPORTANCE** *Streptococcus pyogenes* is restricted to human hosts and commonly causes superficial diseases such as pharyngitis; it can also cause severe and deadly manifestations including necrotizing skin disease or severe postinfectious sequelae like rheumatic heart disease. Understanding the complex mechanisms used by this pathogen to manipulate host defenses could aid in developing new therapeutics to treat infections. Here, we examine the impact of a bacterial cell-cell communication system, which is highly conserved across *S. pyogenes*, on host innate immune responses. We find that *S. pyogenes* uses this system to suppress macrophage proinflammatory cytokine responses *in vitro*. Interference with this communication system could serve as a strategy to disarm bacteria and maintain an effective immune response.

**KEYWORDS** immunosuppression, innate immunity, macrophage, pheromone, biosynthetic gene cluster, NF-κB, TLR, cytokines, macrophages
extracellular signals. QS systems invoke social pressures that result in the synchronization of genetic programs across the population. This synchronization enables bacteria to function as a multicellular group better equipped to perform activities such as forming biofilms, producing virulence factors, or taking up foreign DNA (1).

The bacterium *Streptococcus pyogenes* (group A streptococcus [GAS]) is a serious pathogen responsible for a high global burden of disease, including 616 million annual cases of GAS pharyngitis and 1.78 million annual cases of severe diseases like necrotizing fasciitis, toxic shock syndrome, rheumatic heart disease, and glomerulonephritis (2). GAS utilizes several QS systems, including RopB (Rgg1), Rgg2 or Rgg3 (Rgg2/3), ComR (Rgg4), and Sil. These systems have been shown to regulate virulence factors, biofilm production, competence genes, and invasive disease, respectively (1). Notably, the Rgg2/3 system is conserved across all serotypes of GAS, indicating its importance for GAS survival and making it an attractive system to study.

The transcriptional regulators Rgg2 and Rgg3 respond to two functionally equivalent short hydrophobic peptide ligands (SHP2 and SHP3, collectively referred to as SHP) in a concentration-dependent manner (3, 4). When concentrations of SHP are low, the repressive activity of Rgg3 predominates at target promoters. When SHP reaches a critical concentration (∼1 nM in culture conditions), it binds to Rgg2 and Rgg3, causing inactivation of Rgg3 (leading to derepression of target genes) and activation of Rgg2 (leading to transcriptional activation of target genes). Genetic tools have helped identify two genetic loci that are directly controlled by the Rgg2/3 system: (i) the region adjacent to and including *shp2*, including *spy49_0414c* (*stcA*) and (ii) the region adjacent to and including *shp3* and *spy49_0450-0460*. Rgg2/3-mediated regulation of *stcA* promotes aggregation and biofilm development (two phenotypes that require adhesive surface structures) and resistance to lysozyme (an antimicrobial host factor that targets components of the bacterial cell wall) (3, 5). Because the surface of GAS interfaces with host cells, we hypothesized that Rgg2/3-mediated alterations to GAS would result in altered host immune responses.

Early innate immune responses to GAS are critical for control of infection (6). Pharmacological and genetic depletion studies established the importance of macrophages, dendritic cells (DCs), and neutrophils in initiating the innate immune response against GAS via distinct pathways (6–9). Macrophages are particularly important, as in vivo depletion or blockage of phagocytosis drastically enhance susceptibility of mice to GAS (6, 7). In response to GAS, macrophages upregulate expression of genes involved in inflammation, survival, and production of oxygen radicals, which help them eliminate GAS efficiently (10). Signaling through MyD88 in macrophages and dendritic cells is required for cytokine responses and GAS clearance, illustrating the importance of pathogen sensing through Toll-like receptors (TLRs) and interleukin 1 receptor in response to infection (11–14). Downstream of MyD88, a cascade of events leads to the translocation of NF-κB family proteins to the nucleus, where they regulate expression of genes required to promote inflammation, including cytokines, adhesion molecules, and cell growth or death factors.

Because the Rgg2/3 QS system alters surface properties of GAS, this study aimed to determine the consequence on immune responses using an in vitro infection model. Macrophages were infected with isogenic GAS mutants lacking either the transcriptional repressor, *rgg3* (QS-locked-ON) or the transcriptional activator, *rgg2* (QS-locked-OFF). Here, we report that Rgg2/3 activation limits proinflammatory cytokine responses to GAS. Moreover, QS activation resulted in suppression of cytokine responses induced by several TLR agonists. Expression of the putative biosynthetic gene cluster (BGC) downstream of *shp3* was found to be required for this phenotype. Overall, this study has identified a new role for Rgg2/3 QS in suppressing cytokine responses to GAS in vitro.

**RESULTS**

**Macrophage responses to GAS are attenuated when Rgg2/3 QS is active.** Macrophages respond to GAS in part by activating NF-κB, a transcription factor capable of regulating expression of many proinflammatory cytokines. To determine whether
the GAS QS state impacts macrophage responses, proinflammatory responses were measured following in vitro infections with wild-type (WT) (strain NZ131), Δrgg3 (QS-locked-ON), or Δrgg2 (QS-locked-OFF) GAS. Under standard culturing of GAS in a chemically defined medium (CDM) with glucose, the Rgg2/3 QS system remains silent in WT unless exogenous SHP (>1 nM) is supplemented (3), the endopeptidase PepO is inactivated (15, 16), or specialized conditions are met (i.e., mannose is substituted as the carbon source or if manganese or iron are depleted) (17). As expected, infection of macrophages with WT or Δrgg2 GAS grown in CDM resulted in macrophage stimulation, as indicated by activation of NF-κB and production of large amounts of tumor necrosis factor alpha (TNF-α) and interleukin 6 (IL-6) (Fig. 1A and B). Surprisingly, infection with the Δrgg3 mutant led to approximately 4-fold decreased NF-κB reporter activity and 20-fold decreased TNF-α and 25-fold decreased IL-6 production compared to infection with WT or Δrgg2 strain (Fig. 1A and B). To determine whether decreased activity was due to differences in macrophage cytotoxicity, extracellular release of the cytoplasmic enzyme lactate dehydrogenase (LDH) was measured as an indicator of plasma membrane damage. LDH release was minimal in response to WT and mutant GAS strains after 8 h of infection (Fig. 1C). Additionally, infecting macrophages with increasing multiplicities (MOIs) of the Δrgg2 mutant resulted in dose-dependent activation of NF-κB (Fig. 1D). Increasing the MOI of the Δrgg3 mutant, however, failed to increase NF-κB responses, and instead they remained attenuated even at the highest MOI tested. Whereas macrophages were stimulated by WT GAS grown in nonsupplemented CDM, macrophages infected with SHP-activated WT GAS led to attenuated TNF-α production similar to that of the genetically established QS-locked-ON mutant, the Δrgg3 mutant (Fig. 1E). Macrophage responses to WT GAS grown in the presence of the inactive peptide that contains the reversed sequence of SHP (revSHP) mimicked that of the genetically established QS-locked-OFF mutant, the Δrgg2 mutant.

Rgg2/3 QS is conserved across all sequenced serotypes of GAS. GAS serotypes are classified based on differences in the M protein, a surface protein, and a major virulence factor. The NZ131 strain (serotype M49) was used for a majority of this work because it is a highly transformable strain and excellent tool for genetic manipulation of GAS. To confirm that the immunomodulatory phenotype is not restricted to strain NZ131, macrophage TNF-α responses were measured following infection with other wild-type strains: HSC5 (M14), 5448 (M1), and MGAS315 (M3). These particular strains were chosen as representatives of diverse M types. Furthermore, we confirmed previously that Rgg2/3 activation leads to cell surface changes (lysozyme resistance and biofilm formation) in both HSC5 and MGAS315 strains (17). Strain 5448 was added as a representative M1T1 globally disseminated, clinically relevant strain. With the exception of MGAS315, activation of Rgg2/3 QS by the addition of exogenous SHP resulted in reduced macrophage TNF-α production in response to all other strains tested (Fig. 1E).

Curiously, minimal TNF-α was produced in response to strain MGAS315, even without the activation of QS. We hypothesized that this may be due to the strain’s high expression of capsule, a virulence factor that prevents adherence and phagocytosis (18). However, treatment of MGAS315 with hyaluronidase, an enzyme capable of cleaving the hyaluronic acid capsule, failed to increase the NF-κB response to Δrgg2 or Δrgg3 MGAS315 (see Fig. S1A, Δrgg2-H and Δrgg3-H, in the supplemental material).

To determine whether the differential cytokine response is restricted to RAW264.7 macrophages, the effect of QS activation on cytokine production was also examined following in vitro infection of primary mouse bone marrow-derived macrophages (BMDM) and dendritic cells (BMDC), as well as phorbol myristate acetate (PMA)-differentiated THP-1 human monocyte cells. TNF-α production by BMDM, BMDC, and THP-1 cells was attenuated in response to the Δrgg3 mutant, consistent with responses seen in RAW264.7 cells (Fig. 1F). These data suggest that the Δrgg3 mutant is able to manipulate cytokine production in multiple innate immune cell types, including human
macrophages, indicating the potential relevance and applicability of interfering with QS as a therapeutic strategy.

**QS-ON GAS actively suppresses macrophage inflammatory responses.** To distinguish between the possibilities that QS-activated GAS either passively evades detection (i.e., hides) or actively downregulates (i.e., suppresses) inflammatory responses, macrophages were infected with mixed populations of Δrgg3 and Δrgg2 mutants, and NF-κB activity and cytokine production were measured. Following mixed infection with both Δrgg3 and Δrgg2 mutants, NF-κB activity remained low and was similar to that of Δrgg3 single infection (Fig. 2A). Decreasing the ratio of the Δrgg3 to Δrgg2 mutant (by...
decreasing the MOI of the Δrgg3 mutant) in mixed infections led to a dose-dependent increase in production of all cytokines tested (TNF-α, IL-6, and interferon beta [IFN-β]). Surprisingly, cytokine production remained attenuated even when the Δrgg3 mutant was outnumbered 5 to 1 by the Δrgg2 mutant (Fig. 2B). TNF-α production by primary mouse BMDM and BMDC and human THP-1 cells was also attenuated following mixed infections with equal MOIs of Δrgg2 and Δrgg3 GAS or WT GAS grown in the presence of SHP (Fig. 2C). Together, these data suggest that QS enables GAS to suppress macrophage cytokine responses.

Because infecting macrophages with MGAS315 elicited low TNF-α production (Fig. 1E), we wondered whether this strain could suppress macrophage responses irrespective of the QS state. MGAS315 strains lacking rgg3 or rgg2 were used to determine the effect on cytokine production in mixed infections; the QS-OFF strain (Δrgg2-NZ131 background) was used to elicit TNF-α responses. Similar to WT MGAS315 (Fig. 1E), single infections with either the Δrgg2 or Δrgg3 mutant resulted in undetectable TNF-α production (data not shown). Mixed infections resulted in minor amounts of suppression, independent of the QS state (Fig. S1B). Again, we wondered if high levels of capsule on MGAS315 prohibited the suppressive capacity in this strain and therefore treated cultures with hyaluronidase, confirming the loss of capsule by the ability to pellet cells after brief centrifugation. However, hyaluronidase treatment of strain MGAS315 did not potentiate QS-ON GAS to suppress (Fig. S1C), indicating that MGAS315 is unique among strains tested in that it cannot utilize QS to suppress NF-κB or TNF-α responses.

**FIG 2** QS-ON GAS actively suppresses inflammatory responses. (A) NF-κB activity after infecting RAW-Blue cells with Δrgg2 or Δrgg3 GAS or both. (B) TNF-α, IL-6, and IFN-β production after RAW264.7 cells were infected with the described MOIs of Δrgg2 and Δrgg3 GAS. (C) TNF-α production by BMDM, BMDC, and THP-1 cells (BMDM, BMDC) or 12 (THP-1) h after infection at an MOI of 10 of Δrgg2 GAS or coinfected with an MOI of 10 of each Δrgg2 and Δrgg3 GAS or Δrgg2 and WT GAS grown in the presence of SHP. (D) TNF-α production after RAW264.7 cells were coinfected with TLR agonists and Δrgg3 or Δrgg2 GAS. LPS, lipopolysaccharide (TLR4); HKLM, heat-killed Listeria monocytogenes (TLR2); ODN1826, CpG oligodeoxynucleotide (TLR9). Means plus SD are shown from a representative of two (D) or three (A to C) independent experiments conducted in triplicate. *, P < 0.05; **, P < 0.005; ***, P < 0.001; ****, P < 0.0001, by ordinary one-way ANOVA with Tukey’s multiple-comparison test (A to C) or two-way ANOVA with Sidak’s multiple-comparison test (D).
The specific pathogen-associated molecular patterns (PAMPs) responsible for inducing proinflammatory responses to GAS are incompletely described; however, it has been well established that both the MyD88–NF-κB pathway and the type I IFN pathway are required for clearance (12, 14). We wondered whether QS would enable GAS to suppress stimulation by TLR agonists. TLR agonist-stimulated macrophages produced significantly larger amounts of TNF-α when applied simultaneously with the Δrgg2 mutant (Fig. 2D). However, agonist treatment together with Δrgg3 infection resulted in decreased TNF-α production in response to lipopolysaccharide (LPS; TLR4), heat-killed Listeria monocytogenes (HKLM; TLR2), and CpG oligodeoxynucleotide (ODN1826; TLR9). Together, these data suggest that GAS suppresses NF-κB-mediated proinflammatory responses downstream of TLR stimulation.

Suppression requires contact with live QS-ON GAS. To localize the factor(s) responsible for QS-regulated cytokine modulation, the ability of secreted/extracellular components and surface-associated components to alter NF-κB activity was tested. In other pathogenic bacteria, QS molecules themselves have been shown to possess immunomodulatory properties toward host cells. For example, treatment of epithelial cells with QS molecules produced by Pseudomonas aeruginosa (i.e., homoserine lactones, quinolones, and phenazines) results in differential regulation of cytokine expression via sensing by the host receptor AhR (19). Macrophage treatment with the Rgg2/3 QS molecule SHP failed to increase NF-κB activity compared to untreated controls. Therefore, we tested whether addition of SHP to macrophages infected by the Δrgg2 mutant was sufficient to attenuate NF-κB activity. We saw that addition of 200 nM either SHP or revSHP to macrophages was unable to suppress NF-κB activity (Fig. 3A). These data suggest that although SHP signals induce Rgg2/3 signaling, they are not directly responsible for the observed immunomodulatory effect.

To determine whether other secreted factors could enable QS-ON GAS to suppress NF-κB activity, macrophages were directly stimulated with Δrgg2 GAS, and Δrgg3 GAS was added to macrophages either directly or separated by a 0.4-μm-pore transwell membrane (TW). This pore size prohibits Δrgg3 GAS from directly contacting macrophages while simultaneously allowing secreted factors to pass through the membrane. We determined that when Δrgg3 GAS was added above the TW (Δrgg3-TW), it was unable to suppress NF-κB activity (Fig. 3B, gray bar). This indicated that macrophage suppression is a contact-dependent phenomenon. Furthermore, sterile filtered supernatants from Δrgg3 cultures were added to macrophages infected with Δrgg2 GAS and failed to suppress NF-κB activity, further indicating that GAS culture supernatants lack the factor responsible for suppressing macrophage responses (Fig. 3C).

Our previous work illustrated that cell surface properties of GAS are altered via Rgg2/3 QS (3, 5, 17). To examine whether these surface changes include alterations of the repertoire or display of antigens, macrophages were infected with GAS inactivated by different methods, including heat (heat killed [HK]), short wave UV light (UV), and 4% paraformaldehyde (PFA) treatment. While heat has been shown to alter cell wall peptidoglycans and denature proteins, UV treatment damages DNA and RNA and is less likely to interfere with cell surface properties. PFA treatment cross-links amines in proteins and other structures within the cell. We posited that if QS-induced surface changes are responsible for altered macrophage responses, infection with inactivated GAS would similarly result in differential inflammatory responses. After each inactivation treatment, bacteria were plated for enumeration to confirm loss of viability, and in each case >99.9% of cells were nonrecoverable. Macrophages infected with inactivated GAS had lower NF-κB activity compared to those infected with live GAS, and this was consistent across all treatments (Fig. 3C). Inactivation of GAS with heat and UV eliminated the QS-dependent differences in NF-κB activity (Fig. 3C). Furthermore, inactivation of Δrgg3 GAS by any treatment eliminated its ability to attenuate NF-κB activity when added to cells stimulated with live, metabolically active Δrgg2 GAS (Fig. 3C). This suggests that alterations in surface properties are unlikely responsible for the differences in macrophage responses to Δrgg3 GAS.
though it is possible that these inactivation methods may have interfered with the unknown ligand responsible for immunosuppression. Cumulatively, these data indicate that immunomodulation by QS-ON GAS requires live bacteria and direct contact between the pathogen and host cells.

**QS does not alter bacterial adherence or internalization.** GAS initially interacts with macrophages through bacterial adherence and internalization. Though initially thought to be an exclusively extracellular pathogen, much evidence has illustrated that GAS can also invade and even replicate intracellularly (20, 21). We found that immunosuppression requires contact, as it does not occur when QS-ON GAS is separated from macrophages by a transwell insert (Fig. 3B). To determine whether adherence to macrophages is altered by QS activity, GAS was plated for CFU enumeration after infection and compared to the initial inoculum. The ΔcovR mutant (NZ131) was utilized as a negative control due to its high level of capsule (an antiphagocytic and anti-adherence factor). Although the ΔcovR mutant was a poor binder, the ability of WT, Δrgg2, and Δrgg3 strains to adhere to macrophages after 30 min was clearly apparent but not significantly different from one another (Fig. S1D) (22).

Macrophages can sense extracellular GAS through various cell surface receptors, but they can also recognize intracellular GAS through cytosolic and endosomal receptors. To determine whether the QS state results in altered internalization or intracellular
survival in macrophages, viable GAS was measured over time after gentamicin treatment. Both Δrgg2 and Δrgg3 bacteria were internalized to similar levels, and at hourly intervals following gentamicin treatment, we found that the numbers of viable bacteria were reduced at similar rates. Thus, the ability of Δrgg3 bacteria to suppress...
Macrophage activity is not a function of an altered ability to internalize or survive phagocytosis (Fig. S1E).

A QS-regulated operon is required for cytokine suppression. Several virulence factors have been described as important in manipulating immune responses to GAS, including streptolysin O (SLO), S. pyogenes cell envelope protease (SpyCEP), M protein, and capsule, all of which interact with the bacterial surface (23, 24). To test whether any of these components are involved in QS-dependent immunosuppression, we stimulated the Rgg2/3 system by addition of SHP pheromone in isogenic strains lacking SLO (Δslo), capsule (ΔhasAB), M protein (Δemm), or SpyCEP (Δspycep). When QS was stimulated, each mutant maintained its capacity to suppress NF-κB activity in LPS-activated macrophages, indicating that these virulence factors are not involved in the QS-dependent phenotype (Fig. 4A).

The major genetic targets of the Rgg2/3 QS pathway include (i) spy49_0414c, encoding the protein StcA, and (ii) spy49_0450-0460, encoding a putative biosynthetic gene cluster (BGC) (Fig. 4B) (3). We previously reported that activation of Rgg2/3 QS mediates production of biofilms and resistance to the host antimicrobial factor lysozyme, two phenotypes that rely on surface modifications and were shown to require QS regulation of StcA (3, 5). We wondered whether regulation of StcA also enabled suppression of inflammatory pathways in innate immune cells. Macrophages were infected with either Δ0414c or Δ0450-0460 GAS, each grown in the presence of SHP (QS-ON) or inactive revSHP (QS-OFF), and NF-κB activity was evaluated. The outcomes of the infections showed that while spy49_0414c was not required for QS-regulated attenuation of NF-κB activity, spy49_0450-0460 was necessary (Fig. 4C). Further interrogation using isogenic mutants of various genes within this operon determined that QS-ON GAS lacking either the first six genes (spy49_0450-0456) or the second to last gene, spy49_0459, failed to attenuate NF-κB activity following single infections (Fig. 4C). Interestingly, infection with QS-ON GAS lacking only spy49_0460 attenuated NF-κB activity to similar levels as infection with the WT control (Fig. 4C). Consistent with this observation, mixed infections with QS-OFF GAS and WT or BGC mutants grown in the presence of SHP pheromone (QS-ON) demonstrated that BGC mutants significantly restored the NF-κB response, suggesting these genes are involved in suppression (Fig. 4D). Expressing spy49_0450-0457 from an episomal plasmid, or spy49_0459 in single copy from a phage integration site in the chromosome, as a means to complement corresponding gene deletions at the native location was able to restore the suppressive capacity of GAS (Fig. 4E and F). However, complementation of Δ0450-0460 with spy49_0450-0457 failed to fully restore suppression, suggesting that all genes in the BGC (with the exception of spy49_0460) are needed for optimal suppressive activity (Fig. 4F). Together, these data suggest that the...
previously described surface alterations mediated by stcA are not responsible for macrophage suppression by QS-ON GAS and instead genes in the BGC are involved.

**Rgg2/3 QS can be targeted pharmacologically to restore immunity.** The ability of QS-activated GAS to suppress host cytokine responses could be a new potential mechanism to target in vivo as an antivirulence treatment strategy. Previous screening of a library of FDA-approved drugs identified cyclosporine A (CsA) as an inhibitor of Rgg2/3 QS signaling. The CsA analog valspodar, which lacks immunosuppressive effects, was also found to inhibit signaling (25). To determine whether pharmacologically inhibiting QS could prevent immunosuppression, Δrgg3 and Δrgg2 cultures were treated with 10 μM valspodar and then applied to macrophages. Compared with untreated Δrgg3 GAS, valspodar-treated GAS was no longer able to suppress cytokine production in macrophages (Fig. 5). These data indicate that blocking QS signaling can restore macrophage responses to GAS and eliminate their ability to suppress cytokine production.

**DISCUSSION**

This study presents a novel phenomenon whereby GAS utilizes an intercellular regulatory system to actively suppress NF-κB activity and proinflammatory cytokine production in macrophages and dendritic cells. Bacteria incapable of responding to pheromone signals (QS-OFF mutants) lacked the ability to suppress immune cell responses. QS-ON GAS that were inactivated by heat treatment, fixation, or UV irradiation also lost their ability to suppress inflammatory responses. This indicates that suppression is an active process occurring at the interface of GAS and macrophages rather than presentation of a stable surface moiety by GAS. Cell-free culture supernatants also failed to suppress inflammatory responses, further supporting the notion that a secreted factor is not released into the surrounding milieu. Separation of bacteria from stimulated macrophages by a transwell membrane also abolished suppression capacity of QS-ON GAS. Together, these data support a model whereby GAS contacts innate immune cells and, when QS signaling is active, presents or delivers a factor that interrupts host signaling pathways.

The Rgg2/3 QS system directly regulates two operons, each encoding an shp gene and additional coding sequences: spy49_0414c (stcA) and spy49_0450-0460, a putative biosynthetic gene cluster. Here, we were able to link immune cell suppression activity to expression of spy49_0450-0460; deletion of the operon abolished suppression. This locus is conserved across all sequenced GAS genomes and is comprised of 10 genes coexpressed from the shp3 promoter. They encode various enzymes involved in amino acid biosynthesis, sugar metabolism, and capsule biogenesis (Fig. 4B). The operon was found to be repressed by the metal-dependent regulator MtsR, and some of the genes were identified in screens for those involved in invasive infection and survival in blood (26–28). Yet, little remains known about this putative biosynthetic gene cluster, and similar gene sets are seen in only a few other instances in *Streptococcus porcinus*, *Streptococcus pseudoporcinus*, *Salinispora tropica*, and *Bacillus thuringiensis*. Curiously, in *B. thuringiensis*, the homologous gene cluster is implicated in the biosynthesis of a secreted toxin called thuringensin, a nucleoside analog predicted to have cytotoxic activity (29). We observed no cytotoxic impact to macrophages incubated with QS-ON or QS-OFF cells (Fig. 1C); however, we hypothesize that the product of the spy49_0450-0460 gene cluster could be a bioactive molecule produced in response to and directed at macrophages. The last gene of the operon, spy49_0460 (mefE), encodes a putative efflux protein. The presence of this gene in the operon is consistent with the notion that it aids in delivery of a molecule. Surprisingly, however, deletion of mefE did not affect QS-mediated cytokine suppression in macrophages (Fig. 4D), refuting its potential involvement in the observed activity, unless a redundant pathway is capable of releasing a factor.

Bacteria use diverse strategies to modulate host responses. We hypothesize that GAS produces a QS-regulated factor that can manipulate host signaling pathways and
subsequently shape cytokine responses. Upon TLR activation, a cascade of phosphorylation and ubiquitination events leads to degradation of the inhibitor IκB, allowing NF-κB translocation to the nucleus where it regulates transcription. Here, we demonstrate that GAS suppresses stimulation at a step downstream of TLR activation and upstream of NF-κB transcriptional induction. Several examples of NF-κB pathway disruptors have been reported for Gram-negative pathogens and include Yersinia YopJ, Escherichia coli Nle proteins, and Shigella Osp proteins (30). Fewer examples have been reported for Gram-positive pathogens which largely lack specialized secretion systems used to deliver factors directly to host cells. We found that QS-induced suppression of macrophages required contact with live GAS and was not found in supernatants (Fig. 3). This suggests that the factor is not released from bacteria into extracellular spaces, but instead it might be delivered by a mechanism allowing translocation across the host membrane, such as that seen in type III secretion systems (T3SS). In GAS, delivery of the virulence factor NAD-glycohydrolase (Nga) has been shown to occur in a mechanism functionally equivalent to T3SS but requiring the pore-forming toxin SLO for delivery (31, 32). We induced the Rgg2/3 system in a strain lacking SLO (Δslo) and found it maintained its capacity to suppress NF-κB (Fig. 4A). Thus, if Rgg2/3-dependent immune suppression involves a translocated factor, effector delivery may involve uncharacterized delivery mechanisms.

The ability of Staphylococcus aureus, another Gram-positive pathogen, to actively interfere with host signaling components does not necessitate translocation of factors into host cells. For example, staphylococcal superantigen-like protein (SSL3) binds TLR2 and blocks ligand binding and TLR heterodimerization, thereby inhibiting macrophage stimulation (33, 34). Another protein, TirS, blocks TLR-dependent NF-κB activation by mimicking and interfering with host Toll-interleukin 1 receptor (TIR)-containing adaptor proteins (like MyD88), and unlike SSL3, presumably must enter the host cell cytoplasm in order to function (35). How TirS gains access to the host cytosol is unresolved.

Although many GAS virulence factors facilitate immune evasion by various mechanisms, none have been reported to suppress NF-κB responses. Multiple virulence factors in GAS can suppress cytokines posttranslationally. For example, SLO induces host degradation of IL-1β via ubiquitination, and SpyCEP directly degrades IL-8 via proteolytic cleavage (36, 37). Here, we describe a distinct mechanism of suppression upstream of these pathways. Interestingly, inoculation of macrophages with MGAS315 did not induce cytokine responses regardless of the QS state, but it failed to exhibit immunosuppressive capacity (Fig. 1E; see also Fig. S1C in the supplemental material). Further exploration of the differences between the MGAS315 strain and the others could help shed light on the bacterial factors responsible for the differences in macrophage responses. We suspect that differences in capsule, which prevents adherence to host cells, are involved because direct contact was required for suppression (Fig. 3). Though hyaluronidase cleavage of capsule did not potentiate QS-ON MGAS315 to suppress, a capsule mutant should be tested to verify whether this strain lacks the QS-regulated components responsible for immunosuppression. Interestingly, deleting capsule genes in strain NZ131 did not improve suppression compared to the WT, suggesting there may be redundant factors involved.

Rgg2/3 QS is activated in response to environmental conditions found in host mucosal environments, including metal depletion and mannose utilization (17). It remains unclear what benefits are afforded by the additional layer of intercellular communication signaling. We recently demonstrated the importance of Rgg2/3 QS activation in vivo for nasopharyngeal colonization (38). Whether Rgg2/3-mediated immunosuppression was a contributing factor in the observed increased colonization rates of rgg3 mutants (QS-ON) was not a component of these studies, but blocking NF-κB signaling would likely diminish the efficacy of host strategies for bacterial eradication, including production of antimicrobial factors (lysozyme, cationic peptides), induction of autophagic responses, and recruitment of additional phagocytic and cytotoxic immune cells.
Incorporating cell-cell signaling under threatening conditions likely reinforces bacterial compliance to engage defense mechanisms that improve probabilities of survival if immune responses are blunted.

As we gain deeper understanding of how QS systems are used by bacteria to enhance fitness attributes in the context of host colonization and/or infection, the more promising it becomes to target signaling activities pharmacologically as an alternative or supplementary therapeutic approach to antibiotics. We previously determined that the FDA-approved drugs cyclosporine and valspodar have specific inhibitory activities against Rgg2/3 QS (25). We are encouraged by results shown here that blocking QS activity with valspodar abolished its cytokine attenuation effects and restored macrophage inflammatory responses to GAS in vitro. Testing methodologies that incorporate anti-QS therapeutics remains a compelling strategy that could bolster the host’s intended immune response and diminish infections by this global pathogen.

MATERIALS AND METHODS

Bacterial strains. S. pyogenes (group A streptococcus [GAS]) strain NZ131 was used as the parental strain for genetic mutants (constructed as described below). Other GAS strains tested included HSC5, S448, and MGAS315. GAS were routinely grown without shaking at 37°C in Todd-Hewitt broth with 0.2% yeast extract (THY) or on agar plates, or in a chemically defined medium (CDM) containing 1% (wt/vol) glucose (39). To induce Rgg2/3 activation, 100 nM synthetic SHP pheromone or inactive reverse SHP (revSHP) was added to S. pyogenes cultures at an optical density at 600 nm (OD600) of ≈0.1. When appropriate, antibiotics were added at the following concentrations: chloramphenicol (Cm), 3 μg/ml; erythromycin (Erm), 0.5 μg/ml; kanamycin (Kan), 150 μg/ml; spectinomycin (Sp), 100 μg/ml. Starter cultures were utilized to minimize differences in lag phase and were prepared as follows. GAS strains of interest were streaked on THY plates containing the appropriate antibiotics. Single clones were isolated and inoculated into THY containing the appropriate antibiotics. After incubation overnight at 37°C, the cultures were diluted 1:20 into CDM and grown at 37°C to mid-exponential phase (OD600, 0.5 to 0.8). Last, glycerol was added to a final concentration of 20%, and single-use aliquots were stored at −80°C.

Construction of mutant strains and complementation plasmids. All bacterial strains used in this study are described in Table S1 in the supplemental material. Primers used to construct plasmids for gene deletion or complementation are listed in Table S2. All cloning was done using laboratory E. coli cloning strains such as NEB-5a (New England Biolabs) or BH10c (40), with antibiotics added at the following concentrations: Cm, 10 μg/ml; Erm, 500 μg/ml; Sp, 100 μg/ml. To construct gene deletions, sequences flanking the gene of interest were amplified by PCR and ligated into a temperature-sensitive plasmid, pFED760, by restriction enzyme digestion or Gibson assembly. When necessary, antibiotic resistance markers for kanamycin (aphA3) or chloramphenicol (cat) were cloned between the upstream and downstream flanking regions to generate plasmids for selective allelic replacement. Deletion vectors were electroporated into strain NZ131, and a two-step temperature-dependent selection process was used to isolate mutants of interest. Briefly, cells containing each deletion construct were grown at the permissive temperature, then shifted to 37°C, and plated on the appropriate antibiotic to select for bacteria in which the plasmid had integrated at one of the flanking regions. After confirmation of plasmid integration by PCR, cells were grown for ~50 generations at the permissive temperature to allow the plasmid to recombine out, and loss of antibiotic resistance was used to identify the desired mutants. Genotypes were confirmed by PCR. To construct complementation plasmids for BGC mutants, the genomic region encompassing spy49_0450-0457 and its native promoter were amplified by PCR and cloned into a multicopy vector (pLZ12-Sp). For complementation of spy49_0455, the gene was amplified by PCR and cloned downstream of sequence containing ~70 bp of the shpH promoter in an integrating shuttle vector (p7INT/pJC420). Complementation plasmids were confirmed by sequencing.

Cell lines. NF-κB reporter macrophages (RAW-Blue, InvivoGen) were cultured in Dulbecco modified Eagle medium (DMEM) (Gibco) supplemented with 10% fetal bovine serum (FBS) (Gemini, BenchMark), penicillin-streptomycin (P-S) (Corning), and zeocin (InvivoGen), and RAW264.7 macrophages were maintained in RPMI 1640 (Corning) supplemented with 10% FBS and P-S. THP-1 cells were cultured in RPMI 1640 supplemented with 10% FBS, P-S, and 0.05 mM 2-mercaptoethanol. All cell lines were maintained and passaged at 37°C and 5% CO2.

Primary cell culture. BMDM and BMDC were generated from bone marrow precursor cells extracted from the femurs and tibiae of 6- to 8-week-old male or female C57BL/6 mice (Charles River Laboratories).

Synthetic pheromone peptides. Synthetic peptides of 95% purity were purchased from NeoPeptide (Cambridge, MA), reconstituted as 1 mM stocks in dimethyl sulfoxide (DMSO), and stored at −80°C. Dilutions for working stocks were made in DMSO and stored at −20°C. The SHP3-C8 peptide (SHP) sequence is DIIIIVGG, and the reverse peptide (rev-SHP) sequence is GGVIIIID. Synthetic pheromone peptides.

In vitro infections. A total of 2.5 × 104 macrophages were seeded into 24-well tissue culture treated plates (Corning) in 500 μl of medium supplemented with penicillin-streptomycin the day before infection. The following day, medium was aspirated and replaced with medium without antibiotics. GAS was grown from starter cultures in CDM to an OD600 of 0.5 (~2 to 3 h), then normalized based on OD, washed in phosphate-buffered saline (PBS), and added to macrophages. Unless otherwise noted, macrophages were inoculated with GAS at a multiplicity of infection (MOI) of 10:1. Cells were immediately centrifuged...
at 200 × g for 5 min to equilibrate infection and then incubated at 37°C with 5% CO₂. After 30 min, extracellular bacteria were killed by replacing the medium with medium containing 100 μg/ml gentamicin (Gibco). Where applicable, cells were treated with the following TLR agonists from InvivoGen: lipopolysaccharide (LPS) (100 ng/ml), heat-killed Listeria monocytogenes (HKLM) (1 × 10⁵ cells), or CpG oligodeoxynucleotides (ODN1826) (1 μM). For experiments with attenuated GAS, bacteria were killed with heat (65°C), UV (short wave), or 4% PFA for 60 min. For experiments using GAS supernatants, cells were grown to an OD₅₆₀ of ~0.5 and pelleted, and the supernatants were subsequently filtered (0.2 μm) and normalized based on OD. For transwell experiments, 0.4-μm pores (Corning) were used. For hyaluronidase treatment of GAS, 1 × 10⁸ CFU GAS was collected at mid-exponential phase, washed, resuspended in 1 ml of PBS, and treated with 10 U/ml hyaluronidase (Sigma) for 10 min at 37°C. Removal of capsule was confirmed visually by morphological change in the cell pellet after centrifugation. Cells were washed with PBS to remove remaining enzyme and used for infection immediately after.

**Cell viability assay.** Cytotoxicity of macrophages after 8 h of infection was quantified by measuring the release of the enzyme lactate dehydrogenase in cell supernatants using the CytoTox 96 nonradioactive cytotoxicity assay (Promega) according to the manufacturer’s instructions. Percentages were determined by comparing samples with a 100% lysis control.

**NF-κB activation assay.** RAW-Blue macrophages (InvivoGen) with chromosomally integrated NF-κB inducible secreted embryonic alkaline phosphatase (SEAP) reporter construct were used to measure activation of NF-κB. Cells were maintained in DMEM (Gibco) supplemented with 10% heat-inactivated FBS (Gemini), penicillin-streptomycin (Corning), and 200 μg/ml zeocin (InvivoGen) in tissue culture treated T25 flasks (Greiner Bio-One). Cells were grown to 60 to 70% confluence, washed with PBS, and then passaged using 0.05% trypsin - 0.53 mM EDTA (Corning) to dissociate them from the flasks. Reporter macrophages were counted and seeded the day prior to the experiment in flat bottom 96-well tissue culture treated plates at 10⁵ cells/well. The following day, GAS was added to the wells at a multiplicity of infection of 10:1, and cells were centrifuged for 5 min to equilibrate infection. After a 30-min incubation at 37°C, the medium was removed and replaced with medium containing 100 μg/ml gentamicin. After 18 h, RAW-Blue cell-free supernatants were collected, and 50 μl was mixed with 150 μl of the QUANTI-Blue substrate (InvivoGen) and incubated at 37°C for 45 min in a microplate reader (BioTek).

**Generation of bone marrow-derived macrophages and dendritic cells.** Primary murine bone marrow-derived macrophages (BMDM) and dendritic cells (BMDC) were differentiated from bone marrow cells collected from the femurs and tibiae of 6- to 8-week-old male C57BL/6 mice (Charles River Laboratories). For macrophage differentiation, bone marrow was dissociated using 0.05% trypsin for 5 min at 37°C, and then the addition of 400 mM EDTA (Corning) to dissociate them from the bone marrow. Bone marrow-derived macrophages (BMDM) and dendritic cells (BMDC) were differentiated from bone marrow cells by treatment with 5 ng/ml phorbol myristate acetate (PMA) for 48 h, followed by a 24-h recovery period. The purity of BMDMs and BMDCs was measured by cell surface staining and flow cytometry. A total of 2 × 10⁵ cells were transferred to an Eppendorf tube and resuspended in fluorescence-activated cell sorting (FACS) buffer (PBS plus 1% bovine serum albumin (BSA)). Prior to staining, cells were treated with anti-CD16/CD32 (BioLegend) for 15 min to block Fc receptors. Cells were then stained for 1 to 2 min until cells appeared lysed under the microscope. Serial dilutions were plated on THY agar plates and CFU were enumerated after overnight incubation at 37°C with 5% CO₂.

**Measurement of GAS adherence to macrophages.** Adherence to RAW264.7 cells was measured after 30 min of infection. Cells were gently washed three times with 300 μl PBS, followed by incubation with 100 μl trypsin for 5 min at 37°C, and then the addition of 400 μl of 0.1% saponin in sterile water for 1 to 2 min until cells appeared lysed under the microscope. Serial dilutions were plated on THY agar plates and CFU were enumerated after overnight incubation at 37°C with 5% CO₂.

**Measurement of GAS internalization by macrophages.** Viable internalized GAS was measured by gentamicin protection assay. Briefly, RAW264.7 or RAW-Blue cells were infected at an MOI of 10 for 30 min. Medium was aspirated and replaced with medium containing 100 μg/ml gentamicin. Cells were further incubated for 1 to 4 h. Wells were gently washed three times with 500 μl PBS, followed by incubation with 100 μl trypsin for 5 min at 37°C and then addition of 400 μl of 0.1% saponin in sterile water for...
REFERENCES


SUPPLEMENTAL MATERIAL

Supplemental material is available online only.

FIG S1, TIF file, 1.5 MB.
TABLE S1, DOCX file, 0.03 MB.
TABLE S2, DOCX file, 0.02 MB.

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We declare that we have no competing interests.

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