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Regulation of Hypercompetence in *Legionella pneumophila*

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Although many bacteria are known to be naturally competent for DNA uptake, this ability varies dramatically between species and even within a single species, some isolates display high levels of competence while others seem to be completely nontransformable. Surprisingly, many nontransformable bacterial strains appear to encode components necessary for DNA uptake. We believe that many such strains are actually competent but that this ability has been overlooked because standard laboratory conditions are inappropriate for competence induction. For example, most strains of the gram-negative bacterium *Legionella pneumophila* are not competent under normal laboratory conditions of aerobic growth at 37°C. However, it was previously reported that microaerophilic growth at 37°C allows *L. pneumophila* serogroup 1 strain AA100 to be naturally transformed. Here we report that another *L. pneumophila* serogroup 1 strain, Lp02, can also be transformed under these conditions. Moreover, Lp02 can be induced to high levels of competence by a second set of conditions, aerobic growth at 30°C. In contrast to Lp02, AA100 is only minimally transformable at 30°C, indicating that Lp02 is hypercompetent under these conditions. To identify potential causes of hypercompetence, we isolated mutants of AA100 that exhibited enhanced DNA uptake. Characterization of these mutants revealed two genes, *proQ* and *comR*, that are involved in regulating competence in *L. pneumophila*. This approach, involving the isolation of hypercompetent mutants, shows great promise as a method for identifying natural transformation in bacterial species previously thought to be nontransformable.

The phenomenon of natural transformation, also known as competence, is defined as the ability of bacteria to take up and stably maintain exogenous DNA. This ability is prevalent in nature, as evidenced by the description of natural competence in over 40 different bacterial species, which are widely distributed among taxonomic and trophic groups (reviewed in reference 31). Although the purpose of natural transformation in nature remains unknown, it has been speculated to provide a means of genetic exchange, DNA repair, and/or nutrient acquisition (31).

The numerous examples of naturally transformable bacteria in the environment suggest that competence is a widely conserved trait, and yet, surprisingly, many bacterial species seem to lack this ability. Even closely related strains within a competent species can exhibit profound differences in the competence phenotype. For example, examination of a worldwide collection of *Pseudomonas stutzeri* strains revealed that less than one half were competent (45). In a similar analysis of *Actinobacillus actinomycetemcomitans* strains, only 1 of 17 was found to be transformable (52). Curiously, many bacteria that do not appear to be competent are known to encode components of DNA uptake machinery (9). It is possible that some of these strains contain only remnants of a once-functional uptake apparatus. Alternatively, they may actually be competent in the environment but have lost this ability due to passage in the laboratory. Finally, bacterial strains fully capable of natural transformation may only appear to be noncompetent due to the use of inappropriate assay conditions.

Consistent with the latter possibility, the ability to take up DNA is generally not constitutive but requires the development of a specific, genetically programmed physiological state (13). Moreover, development of the competent state varies greatly between organisms, making prediction of competence-inducing conditions difficult. For example, in *Streptococcus pneumoniae* competence is expressed transiently during the exponential phase of growth, when nutrients are plentiful, and is repressed in stationary phase (38, 48). In contrast, competence in *Bacillus subtilis* occurs in response to starvation and does not become apparent until the late exponential phase of growth (29). In each of these gram-positive species, the regulation of competence is mediated by quorum sensing (21, 46). Gram-negative species such as *Neisseria gonorrhoeae*, *Haemophilus influenzae*, and *Acinetobacter calcoaceticus* also display varied relationships between transformation and growth phase but do not use quorum sensing to induce the competent state (5, 17, 31, 40). From these studies, it is clear that induction of competence is highly variable, and for this reason many bacterial species capable of natural transformation may have yet to be recognized as such.

The gram-negative bacterium *Legionella pneumophila* provides an example of a competent species in which the transformable phenotype remained undiscovered due to a requirement for unusual inducing conditions. For over 20 years, *L. pneumophila* was not believed to be naturally competent. Recently, however, it was discovered that the *L. pneumophila* serogroup 1 strain AA100 can be transformed using microaerophilic growth at 37°C (47). In contrast, AA100 cannot be transformed using aerobic growth at 37°C, conditions normally used to culture *L. pneumophila*.

While investigating methods to induce competence in the laboratory setting, we discovered that another *L. pneumophila*
serogroup 1 strain, Lp02, displays an unusually high level of competence at 30°C. The phenotype of enhanced competence, termed hypercompetence, has been described previously for bacterial mutants with defects in regulatory factors that increase or deregulate expression of the competence regulon (24, 28, 33, 49, 53). Hypercompetence can also result from mutations in components of the uptake machinery, as seen in P. stutzeri (18). Finally, hypercompetence can be induced indirectly: for example, an H. influenzae mutant with an altered peptidoglycan biosynthesis gene causes induction of the normal competence pathway (32).

We demonstrate here that Lp02 exhibits a hypercompetence phenotype at 30°C that is both growth phase and temperature regulated. In addition, we were able to recapitulate the hypercompetent phenotype in AA100 using mutagenesis and selection. Examination of AA100 hypercompetent mutant strains revealed two genes, proQ and comR, that normally repress natural transformation in L. pneumophila. The identification of highly transformable L. pneumophila strains could provide a useful tool for rapid and efficient genetic manipulation of this pathogen.

MATERIALS AND METHODS

Bacterial strains and media. Bacterial strains are listed in Table 1. Strain AA100 is a streptomycin-resistant derivative of an L. pneumophila serogroup 1 clinical isolate (1). Strain Lp02 is a derivative of the L. pneumophila serogroup 1 clinical isolate Philadelphia-1 (3). All L. pneumophila strains were cultured on N-2-acetamido-2-aminoethanesulfonic acid (ACES)-buffered charcoal yeast extract broth (CYE) or in ACES-buffered yeast extract broth (AYE) as described previously (15, 16). Lp02 and Lp02 derivatives were cultured on CYE or AYE supplemented with 100 μg of thymidine/ml. Kanamycin, chloramphenicol, and gentamicin were used at 30, 5, and 6.5 μg/ml, respectively.

Strain and plasmid construction. Plasmids for natural competence reporter systems were built by first cloning a region of the Lp02 chromosome into pBlueScript II KS+. This study

TABLE 1. Bacterial strains and plasmids

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<thead>
<tr>
<th>Strain or plasmid</th>
<th>Relevant property(ies)</th>
<th>Reference or source</th>
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</thead>
<tbody>
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</tr>
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<td>JV1103</td>
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<td>JV1160</td>
<td>Lp02 Kan′r</td>
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<tr>
<td>JV1727</td>
<td>AA100 comR::mini-Tn10kan</td>
<td>This study</td>
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<td>JV1729</td>
<td>AA100 proQ::mini-Tn10kan</td>
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<td>JV1763</td>
<td>JV1727 + vector</td>
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<td>JV1727 + Lp02 comR</td>
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<td>recA1 endA1 gyrA96 thi1 hsdR17 supE44 relA1 lac [F' proAB lac' ZΔM15 Tn10 (Tc′)]</td>
<td>Stratagene (La Jolla, Calif.)</td>
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<td>pSC101 cloning vector</td>
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<td>pJB955, Kan′r in center of insert</td>
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<td>pJB908 derivative</td>
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<td>p34S-Gm</td>
<td>Cloning vector with Gent′r cassette</td>
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<td>RSF1010 cloning vector, Gent′r</td>
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<td>pJB1653, proQ′ (from strain Lp02)</td>
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<td>pJB1653, comR′ (from strain Lp02)</td>
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</tr>
<tr>
<td>pJB1665</td>
<td>pJB1653, comR′ (from strain AA100)</td>
<td>This study</td>
</tr>
</tbody>
</table>

* CDC, Centers for Disease Control and Prevention.

Downloaded from http://jb.asm.org/ on April 22, 2014 by Washington University in St. Louis
(respectively) cloned into a HindIII site in the pJB955 insert. Complementary strains were constructed by naturally transforming the wild-type L. pneumophila strain Lp02 with reporter plasmid pJB957 or pJB964. This resulted in strains with a Kan′ or Cm′ cassette inserted on the chromosome in the HindIII site adjacent to the desired region. The Kan′ and Cm′ strains were calculated to be JV1103 and JV1160, respectively, and their phenotypes were confirmed by Southern blotting.

The cloning vector pJB1653, used to create proQ and comR complementing clones, is a Gent′ derivative of the RSF1010 cloning vector pJB908 (43). First, the pJB908 polynucleotide HindIII site was replaced with a NotI site, creating plasmid pJB908R. Plasmid pJB908R was then digested with NotI, the cohesive ends were filled in using Klenow polymerase, and the Gent′ cassette from plasmid p345-Gm (12) was cloned into this site to make plasmid pJB1653. pJB1659, pJB1661, and pJB1665 complementing clones were created as follows: the proQ or comR open reading frames were PCR amplified from chromosomal DNA of the appropriate strain with primers containing BamHI or Sall restriction sites. Primers were as follows: proQ, 5′-CCGAGGATCTCCGACTAAAACAAATAAGGGTACC-3′; and comR, 5′-CCGCGGATCCCTTGTTGTGTTTCC-3′.

To compare transformation frequencies between L. pneumophila strain Lp02 and Philadelphia-1 derivatives, the location of the mini-Tn10 insertion was determined by recovering the transposon and its flanking chromosomal DNA as a plasmid (as follows) and then sequencing the flanking regions. Chromosomal DNA from a transposon mutant was digested with restriction endonucleases that do not recognize sites within the transposon. Digested DNA was then circularized via ligation and electroporated into Escherichia coli strain DH5α::proQ. Transformed bacteria containing DNA with the mini-Tn10 transposon were selected for, as the R6K origin contained within the transposon allowed replication of these circularized fragments as plasmids, and the kanamycin resistance marker on the transposon allowed a direct selection for such plasmids. Recovered plasmids were sequenced using primers that hybridized to the ends of the transposon.

RESULTS

Competence in L. pneumophila strain Lp02 is temperature dependent. L. pneumophila was not believed to be naturally competent until recently, when transformation was described for the serogroup 1 strain AA100 (47). Transformation of this strain was found to be dependent upon microaerophilic growth, a condition not normally used to culture L. pneumophila, which may explain why competence went undetected for over 20 years (47). In addition to AA100, a number of laboratories use derivatives of L. pneumophila Philadelphia-1, a strain not previously described as competent. While determining whether Philadelphia-1 derivatives could be transformed using the conditions described for AA100, we discovered that the wild-type laboratory strain Lp02 was able to incorporate a marker at efficiencies comparable to those previously reported for AA100 (data not shown).

With the goals of facilitating genetic screens and enabling high-throughput genomic analysis using natural transformation, we reexamined the published transformation protocol in order to potentially improve its efficiency. First, we generated a set of reporter plasmids and Lp02-derived strains with which to easily assay transformation. The reporter plasmids contained several kilobases of Lp02 DNA interrupted with a drug resistance marker that could be selected for in L. pneumophila (Fig. 1A). The reporter strains contained an insertion with a different drug resistance marker in the corresponding region of the chromosome (Fig. 1B). The site of insertion is in a presumably neutral location immediately downstream of the
Characterization of competence in strain Lp02: DNA source and minimum length of homology. Previously it was shown that AA100 could be transformed both by L. pneumophila chromosomal DNA and by L. pneumophila DNA contained on a plasmid (47). To determine if the 30°C plate transformation assay was comparable in this regard, the effect of DNA source and quantity on the transformation frequency of Lp02 was examined. Similar to AA100, Lp02 could be transformed with either chromosomal DNA or plasmid DNA. For both plasmid and chromosomal DNA, a linear relationship between DNA quantity and transformation frequency was observed (Fig. 3), with average values of 3 × 10^7 transformants per μg of plasmid DNA and 4 × 10^6 transformants per μg of chromosomal DNA. Transformants could be detected using as little as 10 pg of plasmid pJB957, and frequencies of up to 1 in 100 were obtainable with 10 μg of plasmid DNA (Fig. 3A). Interestingly, this amount of plasmid DNA did not appear to be saturating. Similarly, as much as 30 μg of chromosomal DNA from the Kan' strain JV1160 was not sufficient to saturate the reaction (Fig. 3B). Since comparison of the same mass of plasmid and chromosomal DNA was equivalent to using a 1,000-fold molar excess of plasmid DNA, the overall transformation frequencies for plasmid and chromosomal DNA are actually quite similar. Therefore, L. pneumophila is able to take up the two substrates with approximately equal efficiencies.

To optimize this protocol, identical transformation reactions were performed at various temperatures for several days until a patch of growth was apparent. The cells were swabbed into water, serially diluted, and plated on media selective for the reporter plasmid as well as nonselective media to determine total numbers of bacteria. We found that the Cm' Lp02 derivative strain JV1103 could be transformed with 200 ng of the Kan' reporter plasmid pJB957 at rates approaching 1 transformant per 1,000 total cells (Fig. 2), which was equivalent to ~10^7 transformants per μg of DNA. This level of transformation was approximately 100-fold higher than what Stone and Abu Kwaik found for strain AA100 (47) or what we obtained for strain Lp02 using their published protocol (data not shown). We found that transformation of Lp02 required a temperature between 26 and 34°C, with maximal transformation occurring at 26°C (Fig. 2). Reactions at 37°C yielded no Kan' transformants, similar to assays performed in the absence of transforming DNA. Because L. pneumophila growth at 30°C is more than twice as fast as growth at 26°C, assays were henceforth performed at 30°C. Transformation at this temperature occurred with high fidelity, since 97% of the transformants were the result of homologous recombination at the intended locus resulting in gene replacement. These results suggest that transformation of the L. pneumophila strain Lp02 occurs with high fidelity and is regulated by temperature, consistent with the known temperature regulation of L. pneumophila type IV pilus expression.

Characterization of competence in strain Lp02: DNA source and minimum length of homology. Previously it was shown that AA100 could be transformed both by L. pneumophila chromosomal DNA and by L. pneumophila DNA contained on a plasmid (47). To determine if the 30°C plate transformation assay was comparable in this regard, the effect of DNA source and quantity on the transformation frequency of Lp02 was examined. Similar to AA100, Lp02 could be transformed with either chromosomal DNA or plasmid DNA. For both plasmid and chromosomal DNA, a linear relationship between DNA quantity and transformation frequency was observed (Fig. 3), with average values of 3 × 10^7 transformants per μg of plasmid DNA and 4 × 10^6 transformants per μg of chromosomal DNA. Transformants could be detected using as little as 10 pg of plasmid pJB957, and frequencies of up to 1 in 100 were obtainable with 10 μg of plasmid DNA (Fig. 3A). Interestingly, this amount of plasmid DNA did not appear to be saturating. Similarly, as much as 30 μg of chromosomal DNA from the Kan' strain JV1160 was not sufficient to saturate the reaction (Fig. 3B). Since comparison of the same mass of plasmid and chromosomal DNA was equivalent to using a 1,000-fold molar excess of plasmid DNA, the overall transformation frequencies for plasmid and chromosomal DNA are actually quite similar. Therefore, L. pneumophila is able to take up the two substrates with approximately equal efficiencies.

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A second predicted parameter of transformation is the length of DNA available for homologous recombination. In order to identify the minimum length of homologous DNA sufficient for transformation via natural competence, a series of constructs was made that contained various amounts of *L. pneumophila* DNA flanking a selectable marker (Kan r). We were unable to detect transformation with linear DNA fragments containing 80 or 250 bp of flanking homologous sequence but could detect transformation with linear fragments containing 500 or 1,500 bp of flanking sequence (Fig. 4). When the DNA fragments were present on a closed circular plasmid, transformants were then obtainable with only 250 bp of flanking sequence. In addition, the use of circular rather than linear DNA increased the overall frequency of transformation 10- to 100-fold when 500 or 1,000 bp of flanking sequence was used (Fig. 4), presumably due to increased protection of the circular form from degradation.

**Characterization of competence in strain Lp02: kinetics of DNA uptake.** Another characteristic of natural competence is that uptake of DNA is thought to occur rapidly. DNA is first bound to the bacterial cell and then transported across the cell wall into the cytoplasm, where one strand is integrated onto the bacterial chromosome (20, 25). Because incoming DNA is converted into a DNase-protected state prior to integration, the rate of uptake can be easily measured. To assess the rate...
pacity with which Lp02 can bind and protect transforming DNA, we switched to a 30°C liquid assay where a broth-grown exponential JV1103 culture was incubated with the reporter plasmid pJB957 for various amounts of time. The reaction was terminated by addition of DNase I, which cleaves any free, unprotected DNA (see Materials and Methods). DNA uptake into JV1103 was extremely rapid since addition of DNase immediately after exposure to DNA still resulted in detectable transformants (Fig. 5). As expected, levels of transformation increased linearly with time of exposure to DNA.

Characterization of competence in strain Lp02: growth phase regulation. To further understand the requirements for transformation, assays were performed using a liquid culture. Fresh medium was inoculated with cells from a stationary-phase culture of JV1103 and incubated at 30°C with gentle shaking. Periodically, cells were removed, the optical density of the culture was measured, and 1 μg of DNA was added. The cells and DNA were incubated for 2 h at 30°C with shaking prior to plating on selective medium to assay competence. Consistent with the previous experiment, the frequency of transformation steadily increased during the early exponential phase of growth, peaking at mid-exponential phase. It then dropped precipitously, decreasing to below detectable limits upon entrance into stationary phase (Fig. 6B). Thus, Lp02 competence is not only temperature but also growth phase regulated in both the plate and liquid assays.

Growth phase regulation of natural competence in Lp02 is not due to quorum sensing. Lp02 is maximally competent during early exponential phase and completely nontransformable in late exponential and stationary phase. This growth phase regulation would be consistent with a quorum sensing mechanism, which is commonly used by microorganisms. For example, B. subtilis and S. pneumoniae regulate competence in a growth phase-dependent manner by sensing the presence of secreted peptide pheromones in the medium (21, 46). To determine if L. pneumophila is regulating competence via quorum sensing, cells were removed from an exponential-phase liquid culture, gently pelleted, resuspended in fresh medium or in conditioned medium from a stationary-phase JV1103 culture, and exposed to pJB957 DNA and the transformation frequency was determined. Addition of fresh medium had no effect on the transformability of exponential cells, whereas addition of conditioned medium completely abolished trans-
formation, consistent with the presence of a factor used for quorum sensing (Fig. 7A).

However, the inhibitory effect of conditioned medium could also be due to changes caused by bacterial growth. To examine whether pH changes in the medium could alter the transformability of *L. pneumophila*, cells were removed from an exponential-phase liquid culture, gently pelleted, resuspended in fresh medium varying from pH 6.0 to 9.0 for 2 h, and then assayed for competence. Normal AYE-thymidine (AYET) is buffered to a pH of 6.9, and *Lp02* was seen to be maximally transformable at this pH (Fig. 7B). Not surprisingly, extreme pHs of above 8 or below 6.3 had a pronounced inhibitory effect on transformation. However, conditioned medium had an average pH of 7.4, and this pH was not significantly inhibitory when fresh medium was used (Fig. 7B), suggesting that changes in medium pH due to bacterial growth were not primarily responsible for the inhibitory effect of conditioned medium. Moreover, adjusting the pH of conditioned medium from 7.4 to 6.9 was not sufficient to eliminate competence repression (Fig. 7A), suggesting the presence of another factor in conditioned medium which regulates competence.

In addition to changes in pH, conditioned medium is significantly different from fresh medium due to a depletion of nutrients. To determine whether a decrease in nutrient availability might also contribute to competence regulation, we exposed exponential-phase bacteria to conditioned medium versus conditioned medium supplemented with yeast extract (see Materials and Methods). The addition of nutrients greatly reduced the effects of conditioned medium on competence, though it did not completely eliminate them (Fig. 7A). However, when the pH of conditioned medium was also adjusted, the frequency of transformation for bacteria exposed to this
medium was very similar to that of bacteria exposed to fresh medium. Thus, growth phase-dependent regulation of competence in L. pneumophila strain Lp02 is not due to the presence of a secreted factor detected by quorum sensing. Instead, it is most likely due to changes in nutrient availability and pH.

Lp02 is unique among several serogroup 1 strains in its ability to be transformed on solid medium. To determine if the ability to be transformed on plates at 30°C was specific to Lp02, a number of commonly used L. pneumophila strains were examined under these conditions. In contrast to our findings with strain Lp02, no transformants could be detected with the serogroup 1 strain AA100 (Fig. 8B), even though it was previously shown to be competent at 37°C under microaerophilic conditions (47). JR32, a strain closely related to Lp02, also did not appear to be competent by the plate assay. Even L. pneumophila Philadelphia-1, the progenitor strain for both Lp02 and JR32, was not transformed via the plate assay (Fig. 8B). Nevertheless, each of these strains was capable of being transformed when assayed for competence by a 30°C liquid assay (Fig. 8C), although Philadelphia-1, JR32, and AA100 were transformed at frequencies reduced by at least 10,000-fold compared to that for Lp02. Thus, strain Lp02 possesses enhanced transformability in these assays and can be described as hypercompetent.

Identification of regulators of competence. Since Lp02 originated from L. pneumophila Philadelphia-1, and neither Philadelphia-1 nor its derivative JR32 displays the level of competence that Lp02 does, we reasoned that the hypercompetence phenotype might have been fortuitously acquired during the derivation of Lp02 from Philadelphia-1. Lp02 was generated by isolating three independent mutations sequentially in L. pneumophila Philadelphia-1. These include spontaneous mutations conferring resistance to streptomycin, a dependence on thymidine supplementation, and a lack of a functional restriction-modification system (3). It is possible that Lp02 acquired mutations in addition to the desired ones while the strain was being passaged. For instance, Lp02 might have lost a factor that normally regulates competence under laboratory conditions, resulting in the hypercompetence phenotype.

To test this possibility, we attempted to identify an inhibitor of natural competence by mutagenizing AA100 with a mini-Tn10 transposon and then selecting for mutant strains that exhibited competence at 30°C on plates (see Materials and Methods). By this approach, two independent mutants, JV1729 and JV1727, were isolated that rendered AA100 amenable to plate transformation although at frequencies 100-fold lower than that of Lp02 (Fig. 9). The first mutant, JV1729, was found to contain an insertion in a gene with homology to the proQ gene of E. coli. E. coli ProQ has been proposed to be a regulator of the osmoprotectant pump ProP (11, 26). The second mutant, JV1727, contained an insertion in a gene which encodes a protein predicted to contain a helix-turn-helix, raising the possibility that it might be a transcriptional regulator. We have named this second gene comR, for competence regulator. In both cases, the transposon insertions were solely responsible for the hypercompetence phenotype, since movement of the insertion into an unmutagenized version of AA100 recapitulated the hypercompetence phenotype in the original strain (data not shown).
Comparison of AA100 and Lp02 proQ. As proQ appears to be a repressor of the competent state in AA100, we reasoned that Lp02 hypercompetence might be due to its inactivation. To test whether the Lp02 proQ gene is functional, we con-

FIG. 8. Lp02 is significantly more competent than other L. pneumophila serogroup 1 strains. (A) Relationship among the three commonly studied L. pneumophila serogroup 1 strains Lp02, JR32, and AA100. Strains Lp02 and JR32 are derivatives of the same parental strain, L. pneumophila Philadelphia-1. AA100 is a derivative of an unrelated serogroup 1 strain, L. pneumophila Wadsworth. (B) Transformation frequency (plate assay) as a function of strain origin. Four L. pneumophila serogroup 1 strains were assayed using the 30°C plate assay. Strains were grown on solid media at 30°C in the presence of 1 μg of reporter construct pJB957 (Kan'). After 48 h, bacteria were plated on selective versus nonselective media in order to determine the number of kanamycin-resistant transformants in the total cell population. The limit of detection for transformation frequency was 10⁻⁹; error bars indicate standard deviations.

FIG. 9. Inactivation of proQ or comR induces competence of strain AA100. (A) Transformation frequency and complementation of strain AA100 containing a proQ mutation. AA100 containing the empty vector pJB1653 (AA100 + vector), AA100 proQ::mini-Tn10kan (JV1729) containing the empty vector pJB1653 (Q' + vector), JV1729 containing the AA100 proQ complementing clone pJB1659 (Q' + QAA100), and JV1729 containing the Lp02 proQ complementing clone pJB1661 (Q' +QLp02) were assayed for the ability to take up pJB964 (Cm') DNA by the 30°C plate assay. (B) Transformation frequency and complementation of strain AA100 containing a comR mutation. AA100 containing the empty vector pJB1653 (AA100 + vector), AA100 comR::mini-Tn10kan (JV1727) containing the empty vector pJB1653 (R' + vector), JV1727 containing the AA100 comR complementing clone pJB1665 (R' + RAA100), and JV1727 containing the Lp02 comR complementing clone pJB1663 (R' + RLP02), were assayed for the ability to take up pJB964 DNA by the 30°C plate assay. (C) Transformation frequency of strain Lp02 in the presence of proQ complementing clones. Lp02 containing the empty vector pJB1653 (Lp02 + vector), the AA100 proQ complementing clone pJB1659 (Lp02 + QAA100), or the Lp02 proQ complementing clone pJB1661 (Lp02 + QLp02) was assayed for the ability to take up pJB964 DNA by the 30°C plate assay. (D) Transformation frequency of strain Lp02 in the presence of comR complementing clones. Lp02 containing either the empty vector pJB1653 (Lp02 + vector), the AA100 comR complementing clone pJB1665 (Lp02 + RAA100), or the Lp02 comR complementing clone pJB1663 (Lp02 + RLP02) was assayed for the ability to take up pJB964. In each transformation reaction, bacteria were exposed to 1 μg of reporter plasmid DNA for 48 h and then plated on selective versus nonselective media in order to determine the number of chloramphenicol-resistant transformants in the total cell population. The limit of detection for transformation frequency was 10⁻⁹; error bars indicate standard deviations.
structured proQ complementing clones from both Lp02 and AA100 DNA, where proQ gene expression is driven by an exogenous promoter. Each clone was transformed into strain JV1729 (AA100 proQ::mini-Tn10kan) in order to check its ability to repress competence. We found that the presence of either Lp02 or AA100 proQ resulted in nearly full repression of JV1729 competence, indicating that each gene could complement the loss of proQ and restore competence inhibition (Fig. 9A). Thus, both Lp02 and AA100 proQ complementing clones appear to encode functional proteins.

Although the Lp02 proQ gene can encode a functional protein in our complementation studies, it is possible that Lp02 does not express sufficient levels of ProQ. For example, Lp02 may contain a proQ promoter mutation or may have lost a positive regulatory factor. To determine if the presence of the proQ complementing clones inhibits Lp02 hypercompetence, we introduced them into this strain and assayed competence. In contrast to JV1729, complete loss of Lp02 hypercompetence in the presence of either clone was not observed (Fig. 9C), suggesting that hypercompetence is not simply due to loss of ProQ activity.

Comparison of AA100 and Lp02 comR. Similar to the case for proQ complementation, the comR insertion strain JV1727 (AA100 comR::mini-Tn10kan) transformed with comR from either Lp02 or AA100 exhibited full competence repression, indicating that both comR complementing clones are functional (Fig. 9B). The presence of comR in strain Lp02 did not fully repress its ability to take up DNA, indicating that Lp02 hypercompetence is not solely due to loss of comR (Fig. 9D). However, a partial decrease in Lp02 transformation frequency was observed in the presence of both comR complementing clones, consistent with a regulatory role for this gene in both AA100 and Lp02 strains.

DISCUSSION

While examining the competence phenotype of the Philadelphia-1 derivative strain Lp02, we discovered that it displays hypercompetence under certain laboratory conditions. Transformation experiments were initially based on previous work demonstrating that a different L. pneumophila serogroup 1 strain, AA100, was able to take up DNA at 37°C under microaerophilic conditions (47). By varying the published protocols, we discovered that Lp02, in contrast to AA100, was highly competent at 30°C with aerobic growth. In an attempt to identify the genetic basis of hypercompetence, we isolated mutant strains of AA100 that exhibit enhanced DNA uptake. Characterization of these mutants revealed two genes, comR and proQ, that repress competence in L. pneumophila.

One striking characteristic of Lp02 hypercompetence is the effect of temperature. Transformation occurs during aerobic growth on agar plates at 30°C, whereas no transformation is observed when the same assay is performed at 37°C. This temperature dependence is consistent with expression studies showing that genes encoding components of the L. pneumophila type IV pili, which is required for transformation, are transcribed at 30 and not at 37°C (30, 47). It is curious that the transformation assays described by Stone and Abu Kwaik were performed at 37°C but clearly depended on the presence of type IV pili (47). A likely explanation for this is that the microaerophilic conditions of their assay induce pilus expression sufficient for transformation. Thus, oxygen availability and temperature are two factors that appear to regulate competence in L. pneumophila.

A linear relationship between plasmid DNA quantity and transformation frequency was observed for both Lp02 and AA100 (47). Whereas we were unable to identify saturating amounts of DNA for Lp02 transformation, Stone and Abu Kwaik found that 8 µg or more was sufficient to saturate AA100 transformation (47). In addition, we noted a correlation between transformation frequency and the length of the DNA substrate. Successful Lp02 transformation depended on the presence of at least 250 bp of flanking DNA and increased proportionally with the length of DNA.

We also discovered that Lp02 competence appears to be controlled by growth phase, with transformation being maximal during exponential growth and completely absent by the beginning of stationary phase. A number of other bacteria exhibit competence during exponential growth, including N. gonorrhoeae, Deinococcus radiodurans, Synechococcus species, and Chlorobium species (31). However, growth phase regulation of Lp02 competence most closely resembles that of A. calcoaceticus, which is maximally transformable in exponential phase and loses competence upon entry into stationary phase (39).

Repression of Lp02 competence during stationary phase results from nutrient depletion and an increase in pH, as the inhibitory effect of conditioned medium can be totally abolished by the addition of yeast extract and lowering of the pH. These data suggest that L. pneumophila does not rely on an extracellular signal molecule such as a quorum sensing autoinducer to regulate the competent state. Alternatively, as proposed for A. calcoaceticus, control of L. pneumophila competence may be under a growth phase-regulated promoter. Another striking example of growth phase regulation in L. pneumophila is the induction of virulence by entry into stationary phase (7, 19). Hammer and Swanson have shown that the stationary-phase induction of virulence traits can be mimicked by artificial expression of the stringent response gene ppGpp synthetase (relA) during exponential phase (19). Furthermore, they have shown that ppGpp production in L. pneumophila is stimulated by conditions of nutrient depletion—the same conditions seen to repress natural competence in this work. It will be important to determine if relA expression might repress competence and/or expression of the type IV pili while inducing virulence.

An initial concern in using natural competence as a genetic tool was the fidelity of the recombination event, particularly because the transformation substrate was often uncut plasmid DNA. In B. subtilis and S. pneumoniae, incoming substrate DNA is cleaved, on average, into ~13.5- or 6-kb fragments (14, 36) of which a single strand is transported across the bacterial membrane while its complement is degraded (14, 27, 34). Similar degradation is thought to occur in the gram-negative species N. gonorrhoeae and H. influenzae (8, 22), and it is likely that L. pneumophila modifies incoming DNA in the same fashion. Despite these modifications, however, reconstitution of plasmids taken up by competence machinery has been shown to occur (2). Though none of the plasmid substrates used in these studies can replicate in L. pneumophila, the possibility of
generating plasmid integrants was a concern. Another concern was the possibility of spontaneous mutation resulting in a strain that might be falsely classified as a transformant. To address these issues, we developed a reporter system with which transformants could be quickly and easily checked for the appropriate recombination event. By this system, the percentage of true transformation for a range of experiments was calculated and found to average 97%. These findings are consistent with those of Stone and Abu Kwaik, who observed a high percentage of homologous transformation with strain AA100 (47). Judging from these results, it is reasonable to conclude that the fidelity of L. pneumophila transformation reactions is high and that the vast majority of natural competence transformants are legitimate.

The discovery that Lp02 is hypercompetent at 30°C compared to its progenitor strain Philadelphia-1 was surprising. The most likely explanation for this observation is that Lp02 was altered during its derivation and rendered hypercompetent. For example, it could have sustained a mutation in a competence regulatory gene resulting in up-regulation of an inducer of competence or loss of a repressor of competence. We favor the latter model since it is more likely and since Lp02 is already known to have sustained at least one deletion during its derivation, resulting in loss of the bvh locus (6, 42).

Based on this idea that competence is normally repressed in L. pneumophila, we attempted to mimic the hypercompetence phenotype of Lp02 in AA100 via gene disruption. The strain pneumophila competence regulator genes, comR and proQ. The comR gene is predicted to encode a novel protein that contains a putative helix-turn-helix motif but has no significant homologies by BLAST search. The presence of a DNA binding motif suggests that this protein may be a novel transcriptional regulator controlling competence in L. pneumophila. The proQ gene encodes a protein with homology to the E. coli ProP protein (26, 35), which functions as a positive regulator on the solute transporter protein ProP (10, 11, 26, 35). E. coli ProP functions in osmoprotection by transporting certain organic solutes such as proline and glycine betaine into cells to maintain a balance of osmotic pressure (reviewed in reference 54). In E. coli, proline uptake by ProP in response to a hypotonic environment is greatly impaired in a proP mutant (10, 11, 26, 35). The fact that disruption of the L. pneumophila AA100 proQ homologue results in increased transformation frequencies suggests a possible relationship between osmolarity and competence regulation.

In order to determine if Lp02 hypercompetence was due to inactivation of proQ, we first tested whether the Lp02 version of this gene could complement the AA100 proQ mutant. The fact that the Lp02 proQ gene could complement indicates that it does not contain a mutation that destroys its activity. Furthermore, expression of proQ from either strain in Lp02 did not fully repress competence, suggesting that Lp02 is not a proQ mutant. Similar to the case with proQ, the comR gene from Lp02 could complement the corresponding AA100 mutant but could not fully repress Lp02 competence, indicating that Lp02 is also not a comR mutant. However, the presence of comR in Lp02 partially inhibited transformation, consistent with its functioning as a competence repressor. Thus, the hypercompetence phenotype of Lp02 does not appear to be due solely to a lesion in one of these regulatory factors and is instead likely caused by a mutation in some third, as yet unidentified, factor.

Natural competence for DNA transformation is an intriguing phenomenon which also has useful genetic applications. Considering that no transducing phage have been discovered for Legionella species, the addition of natural transformation to the genetic armament has been very beneficial. The wild-type laboratory strain Lp02 can be transformed very simply and efficiently, at rates of 10^7 transformants per μg of DNA. Although other commonly used L. pneumophila strains are not naturally competent under the conditions described here, inactivation of the proQ or comR gene could provide an easy method for increasing the competence of AA100, and possibly that of other L. pneumophila species. Further study of strain Lp02 and proQ and comR is likely to lend insight into the complex control pathways for expression of the competent state. Finally, our findings provide further evidence that the competent state is highly regulated and demonstrate that hypercompetence can be easily induced as the result of a single genetic lesion.

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