Isolation and characterization of autolysis-defective mutants of *Escherichia coli* that are resistant to the lytic activity of seminalplasmin

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Two temperature-sensitive autolysis-defective mutants of *Escherichia coli* were isolated and shown to be resistant to lysis induced by seminalplasmin, an antimicrobial protein from bovine seminal plasma, as well as to lysis induced by ampicillin, D-cycloserine and nocardicin, at 37 or 42 °C but not at 30 °C. The mutants were, however, sensitive to inhibition of RNA synthesis by seminalplasmin even at the nonpermissive temperature. Temperature-resistant revertants of the mutants were sensitive to lysis induced by the various antibiotics at 37 or 42 °C. The mutations in both strains were mapped at 58 min on the *E. coli* linkage map. The lysis resistance of the mutants was phenotypically suppressed by the addition of NaCl. Partial suppression of the lysis-resistant phenotype was also observed in a relA genetic background.

Introduction

Seminalplasmin, a 5411 Da basic protein originally isolated as an antibacterial protein from bovine seminal plasma (Reddy & Bhargava, 1979), is now known to have a wide variety of effects on biological systems (Shivaji & Bhargava, 1987; Shivaji *et al.*, 1989). We recently found that seminalplasmin lyases bacteria at concentrations higher than those required for bactericidal activity; characterization of the lytic activity of seminalplasmin led us to the hypothesis that the protein lyases bacteria by activating autolysis (Chitnis *et al.*, 1987).

In order to test our hypothesis and to get an insight into the mechanism of lysis of *Escherichia coli* by seminalplasmin, we have isolated mutants of *E. coli* deficient in autolysis by a procedure similar to that described by Harkness & Ishiguro (1983). The mutants thus obtained were found to be resistant to seminalplasmin-induced lysis. In this paper we describe our studies on these mutants and compare their properties with those of similar mutants isolated earlier (Harkness & Ishiguro, 1983; Shimmin *et al.*, 1984) in the context of regulation of autolysis in *E. coli*.

Methods

*Bacterial and phage strains.* The bacterial strains used in this study were all derivatives of *E. coli* K12. They are described in Table 1. Phage P1-kc, used for transduction, and phage JNK370, used in the TnlO transposition experiments, were from our laboratory stocks.

*Media.* Media used in this study included minimal A, LB (Miller, 1972) and tryptic soy broth (TSB; Hi Media Laboratories, Bombay, India). Media were solidified by the addition of agar (Difco) to a final concentration of 1.5% (w/v). When used, the concentration of tetracycline was 5 µg ml⁻¹ in minimal medium and 15 µg ml⁻¹ in enriched medium.

*Chemicals.* L-Amino acids and D-cycloserine were purchased from Sigma. Nocardicin was a gift from K. Murayama of Fujisawa Pharmaceutical Co. Ltd, Japan. Ampicillin and tetracycline were purchased from local pharmaceutical sources. PHUridine was obtained from Bhabha Atomic Research Centre, Bombay, India. All other chemicals used were of analytical grade.

*Seminalplasmin.* Seminalplasmin was purified from bovine seminal plasma as described earlier (Reddy & Bhargava, 1979); the CM-Sephadex-purified fraction was used in the studies described here.

*Isolation of mutants.* Temperature-sensitive autolysis-defective mutants were isolated by a procedure similar to that described by Harkness & Ishiguro (1983). Strain C90 was mutagenized with ethyl methanesulphonate (Miller, 1972) and the survivors were grown in TSB overnight at 30 °C. The population of mutagenized cells was subcultured and grown at 30 °C to a density of about 1 x 10⁹ cells ml⁻¹. The culture was shifted to 42 °C for 30 min before D-cycloserine was added to a final concentration of 50 µg ml⁻¹. Incubation at 42 °C was continued until no further decrease in OD₆₀₀ could be seen. The surviving cells were collected by centrifugation, washed once with minimal A containing 0.9% NaCl, and grown overnight at 30 °C. The procedure described above was repeated the next day, with the modification that ampicillin at 1 mg ml⁻¹ was used instead of D-cycloserine for inducing lysis at 42 °C, and yet again on the third day, with D-cycloserine.

The survivors of the final D-cycloserine treatment were grown overnight at 30 °C and plated on TSB plates at 30 °C. Individual colonies were then tested for temperature sensitivity (lack of colony...
formation at 42 °C); some of the temperature-sensitive colonies were further purified and screened for resistance to ampicillin- and d-cycloserine-induced lysis.

Genetic techniques. Conjigation was done as described by Miller (1972). Preparation of PIkc lysates and PIkc transduction were performed as described by Gowrishankar (1985). Random transpositions of the tetracycline-resistance transposon, Tn10, were obtained in C90 with the use of the λNK370 lysate, essentially by the method of Kleckner et al. (1978).

Antibiotic-induced lysis. Bacterial cultures were initially grown at 30 °C in a gyratory shaking water bath to an OD₆₀₀ of 0-1-0.25 and then shifted to a shaking water-bath at the desired temperature. After 30 min, the antibiotic was added to the required concentration and lysis was followed by continuously recording the decrease in OD₆₀₀ of the culture incubated in a cuvette maintained at the desired temperature.

Maximum tolerable concentration (MTC). Bacterial cultures were grown at 30 °C in a gyratory shaking water bath to an OD₆₀₀ of 0-1-0.25 and then shifted to a shaking water bath at 42 °C. After 30 min, the antibiotic was added to the desired concentration, incubation continued at 42 °C and lysis followed by measuring the decrease in OD₆₀₀ at various time intervals. MTC is defined as the highest concentration of the antibiotic not causing lysis within 2 h.

RNA synthesis. Exponentially growing E. coli cells (OD₆₀₀ 0-3) were incubated with [³H]uridine (sp. act. 14 Ci mmol⁻¹, 518 GBq mmol⁻¹) at a final concentration of 20 μCi ml⁻¹ in TSB. Samples (0-1 ml) taken at various times were treated with 1 ml cold 10% (w/v) trichloroacetic acid (TCA) followed by 0-5 mg bovine serum albumin. Precipitation was allowed to continue for 30 min and the TCA-insoluble material was collected on Whatman GF/C filter paper discs, washed with cold 5% (w/v) TCA, dried and counted in a toluene-based scintillation fluid.

Results

Isolation of mutants

A mutagenized E. coli culture was subjected to a three-step enrichment procedure to select for temperature-sensitive, lysis-resistant mutants as described in Methods. The mutant culture thus obtained was plated to obtain single colonies, and the individual colonies were tested for temperature sensitivity. Initially, both temperature-resistant and temperature-sensitive colonies were tested for resistance to lysis by ampicillin. Whereas all the 20 temperature-sensitive colonies tested were resistant to lysis by ampicillin, none of the 20 temperature-resistant colonies tested were observed to be so. Two independent isolations were carried out and two mutants (one from each isolation), designated CCMB1001 and CCMB1002, were chosen for further study. The mutant loci in these two strains are tentatively designated as lyt-I and lyt-2 respectively.

Mapping of lyt-I and lyt-2

A Tn10 insertion cotransducible with lyt-I was obtainable as described below. Random transpositions of Tn10 were obtained in E. coli C90 using the phage vector λNK370, as described by Kleckner et al. (1980). A PIkc lysate grown on a population of the Tet' cells was used to transduce the mutant CCMB1001. One of the Tet', temperature-resistant transductants so obtained (CCMB1004) was shown to have a Tn10 insertion with 85% linkage to the wild-type allele corresponding to the lyt-I locus.

Preliminary conjugation experiments between CCMB1004 (itself an HfrC derivative) and CSH57 indicated that the site of Tn10 insertion was between his and argG. More precise mapping was done (i) by interruption mating after transfer of the Tn10 insertion into the Hfr strain KL16, and (ii) by two-factor

<table>
<thead>
<tr>
<th>Strain</th>
<th>Relevant characteristics</th>
<th>Source or reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>C90</td>
<td>ΔproU</td>
<td>Bachmann (1972)</td>
</tr>
<tr>
<td>CSH57</td>
<td>ΔpurE trp his arg met ilv leu thi ara lac Y gal malA xyl mtl rpsL</td>
<td>Miller (1972)</td>
</tr>
<tr>
<td>KL16</td>
<td>ΔproU</td>
<td>Low (1972)</td>
</tr>
<tr>
<td>GI157</td>
<td>ΔproU</td>
<td>Gowrishankar (1985)</td>
</tr>
<tr>
<td>GI216</td>
<td>ΔproU</td>
<td>Gowrishankar (1985)</td>
</tr>
<tr>
<td>GI46</td>
<td>ΔproU</td>
<td>Gowrishankar (1985)</td>
</tr>
<tr>
<td>NF161</td>
<td>ΔproU</td>
<td>This study</td>
</tr>
<tr>
<td>NF162</td>
<td>ΔproU</td>
<td>This study</td>
</tr>
<tr>
<td>CCMB1001</td>
<td>ΔproU</td>
<td>This study</td>
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<tr>
<td>CCMB1002</td>
<td>ΔproU</td>
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<tr>
<td>CCMB1003</td>
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<td>CCMB1004</td>
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<tr>
<td>CCMB1005</td>
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<tr>
<td>CCMB1007</td>
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<tr>
<td>CCMB1008</td>
<td>ΔproU</td>
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*ΔproU is the new name for the osrA locus defined by Gowrishankar (1985).
transductional linkage analysis with the loci srl and proU at 58 min on the E. coli map (Bachmann, 1972; Gowrishanker, 1985). In a cross between CCMB1004 (donor, zf::Tn10) and GJ157 (recipient, proU::lac), 200 out of the 350 Tet' transductants were lac, indicating that the Tn10 insertion in CCMB1004 is 57% cotransducible with proU. In two crosses with CCMB1001 (lyt-1, ts) as recipient and GJ46 (zf-900::Tn10) or GJ216 (srl::Tn10) as donor, 55 out of the 90 Tet' transductants (61%) were temperature resistant in the first case and 40 out of the 75 Tet' transductants (53%) were temperature resistant in the second case, indicating that lyt-1 is linked 61% with the zf-900::Tn10 insertion near proU and 53% with a srl::Tn10 insertion. In accordance with the recommended nomenclature (Chumley et al., 1979), the Tn10 insertion in CCMB1004 has been given the allele number zf-905::Tn10. The above results suggest that lyt-1, along with the closely linked zf-905::Tn10 insertion, lies between the srl and proU loci on the chromosome.

The zf-905::Tn10 insertion was also shown to be 15% cotransducible with lyt-2 in CCMB1002 (data not shown). Since lyt-1 and lyt-2 are, respectively, 85% and 15% linked with this Tn10 insertion, it is possible that the two lyt alleles represent different loci. Complementation tests between them have not been done.

**Resistance to antibiotic-induced lysis**

It is clear from the data shown in Fig. 1 that the mutants CCMB1001 and CCMB1002 were resistant to lysis by both seminalplasmin (200 μg ml⁻¹) and ampicillin (1000 μg ml⁻¹) at 37 °C, the temperature at which the mutants could not form colonies, but not at 30 °C, the temperature at which they could grow and form colonies. Resistance to lysis could be seen in terms both of the time taken for the onset of lysis and of the rate of lysis. Mutant CCMB1002 appeared to be the more resistant to lysis, as it lysed only after about 90 min treatment with ampicillin. At lower concentrations of ampicillin the time taken for the onset of lysis was longer. It is noteworthy that the kinetics of seminalplasmin-induced lysis were very similar to those of ampicillin-induced lysis. The mutants were also similarly resistant to lysis.
induced by two other antibiotics, namely nocardicin and d-cycloserine. Resistance to lysis induced by ampicillin and d-cycloserine could also be seen in terms of the MTC values (Table 2). Here again, CCMB1002 was more resistant than CCMB1001.

As the mutants were resistant to lysis induced by a variety of antibiotics, namely seminalplasmin, ampicillin, d-cycloserine and nocardicin, it was important to see if resistance to lysis induced by all the antibiotics was due to a single mutation. We therefore obtained temperature-resistant revertants of CCMB1001 and CCMB1002 by selecting for colonies that grew at 42 °C; CCMB1003, a revertant of CCMB1001, was studied in detail. The revertant was as sensitive as the wild-type to both seminalplasmin- and ampicillin-induced lysis. Essentially similar results were obtained with d-cycloserine and nocardicin. Two other temperature-resistant revertants of CCMB1001 and three revertants of CCMB1002 were also found to be more sensitive to antibiotic-induced lysis than the mutants from which they were derived.

Since the mutants were resistant to lysis induced by ampicillin, we wanted to see if they would also be resistant to the bactericidal activity of ampicillin. The results in Fig. 2 show that mutant CCMB1001 was indeed resistant to the bactericidal activity of ampicillin. These results are in agreement with earlier observations (Shimmin et al., 1984; Kitano & Tomasz, 1979).

**Table 2. MTC values of ampicillin and d-cycloserine at 42 °C**

<table>
<thead>
<tr>
<th>Strain</th>
<th>Ampicillin (µg ml⁻¹)</th>
<th>D-Cycloserine (µg ml⁻¹)</th>
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<tbody>
<tr>
<td>C90</td>
<td>10</td>
<td>&lt; 50</td>
</tr>
<tr>
<td>CCMB1001</td>
<td>75</td>
<td>2000</td>
</tr>
<tr>
<td>CCMB1002</td>
<td>150</td>
<td>4000</td>
</tr>
</tbody>
</table>

Inhibition of RNA synthesis was shown to be one of the earliest effects of seminalplasmin in E. coli (Reddy & Bhargava, 1978). Our earlier studies (Chitnis et al., 1987) suggested that the inhibitory effect of seminalplasmin upon RNA synthesis occurs independently of its bactericidal effect. We therefore studied the effect of seminalplasmin on RNA synthesis by the mutant strain CCMB1001 at 37 °C (Fig. 3). As one would expect for a temperature-sensitive mutant, the incorporation of [³H]uridine into RNA did not increase exponentially with time. Nevertheless, the inhibitory effect of seminalplasmin on RNA synthesis could be seen even at 3 min, the earliest time studied. This observation supports our view that the inhibition of RNA synthesis by seminal-
Autolysis-defective mutants of *E. coli* 467

Ishiguro and his co-workers had earlier isolated temperature-sensitive mutants of *E. coli* that were resistant to lysis induced by ampicillin and other antibiotics (Harkness & Ishiguro, 1983; Shimmin *et al.*, 1984). The lysis-resistant phenotype of the mutants isolated by Shimmin *et al.* (1984) was found to be suppressed either by the addition of salts such as NaCl or by the presence of a *relA* genotype in the mutant strain (Kusser & Ishiguro, 1987). We therefore determined whether our mutants behaved similarly.

The effect of NaCl on ampicillin-induced lysis of the mutant CCMB1001 is shown in Fig. 4. NaCl at a final concentration of 0.4 M suppressed the lysis-resistant phenotype of the mutant. Further, addition of NaCl to the ampicillin-treated mutant culture resulted in immediate lysis, provided the salt was added at least 20 min after the addition of ampicillin. Similar results were obtained with the mutant CCMB1002 (data not shown). In the case of either mutant, NaCl (0.4 M) had no effect on temperature sensitivity for growth. Similar studies could not be done with seminalplasmin-induced lysis because salts inhibit the lytic activity of seminalplasmin (unpublished results).

In order to study the role of the *relA* gene in antibiotic-induced lysis of the mutants, a P1kc lysate grown on CCMB1005 (*lyt-I* zfr-905 : : Tn10) was used to transduce the isogenic pair of strains NF161 (*relA*+) and NF162 (*relA*) to Tet'. One temperature-sensitive, Tet' transductant was chosen in each case and used to study antibiotic-induced lysis.

Fig. 5 shows seminalplasmin- and ampicillin-induced lysis of *relA*+ and *relA* strains carrying the mutant or wild-type *lyt-I* allele at 37°C. While the *lyt-I*+ *relA*+ (NF-161) and *lyt-I*+ *relA* (NF-162) strains showed little difference in their sensitivity to lysis by seminalplasmin or ampicillin, the *lyt-I relA* strain (CCMB1008) was much more sensitive than the *lyt-I relA*+ strain (CCMB1007). However, the *lyt-I relA* strain did not lyse as well as the *lyt-I*+ strains NF161 and NF162. Essentially similar results were obtained when the antibiotic-induced lysis was studied at 42°C but, as
expected, there was no difference among the four strains when lysis was studied at 30 °C. These results show that the lysis-resistant phenotype was partially suppressed in strains carrying a relA genotype and suggest the involvement of factors other than relA in the lysis resistance of the mutants. Further evidence for the involvement of the relA gene in the lysis resistance of the mutants was obtained by our observation that addition of gentamicin or chloramphenicol, which act as inhibitors of the stringent response, suppressed the lysis resistance of the mutants CCMB1001 and CCMB1002.

Discussion

Comparison with the mutants isolated earlier

The mutants isolated by us resembled those of Shimmin et al. (1984) in that (1) they were temperature-sensitive; (2) they were resistant to lysis only at the nonpermissive temperature (Fig. 1); (3) their degree of lysis resistance depended upon the concentration of the antibiotic used; and (4) their lysis-resistant phenotype was suppressed on addition of NaCl (Fig. 4). The lyt-I mutation mapped at 58 min, as did lytA, the locus to which one of the two sets of mutations obtained by Shimmin et al. (1984) has been assigned (Kusser & Ishiguro, 1987).

However, our mutants differed from those of Shimmin et al. (1984) in that they were much more resistant to D-cycloserine-induced lysis (Table 2); also, their lysis-resistant phenotype was suppressed only partially in the presence of a mutant relA allele or on addition of inhibitors of the stringent response. Thus, in contrast to the results obtained by Kusser & Ishiguro (1987), we found that relA strains carrying a mutant lyt allele were much less sensitive to antibiotic-induced lysis than those carrying the wild-type lyt+ allele (Fig. 5). It remains to be seen whether lyt-I defines a locus different from lytA.

The mutants isolated by Harkness & Ishiguro (1983) differ from our mutants and from those of Shimmin et al. (1984) in that they are not phenotypically suppressed and are not lysed at all, even at high concentrations of antibiotic.

Evidence suggesting defective autolysis in the mutants

As the temperature-resistant revertants showed wild-type characteristics with regard to lysis by the various antibiotics, a single mutation must be responsible for the temperature-dependent lysis resistance of the mutants to the various antibiotics. This observation strongly supports the view that the mutants were defective in autolysis.

We discount decreased permeability as an explanation for the observed lysis-resistant phenotype of the mutants CCMB1001 and CCMB1002, because addition of NaCl to the mutant cultures treated with ampicillin resulted in immediate lysis provided the salt was added 20 min after the addition of the antibiotic. The fact that the mutants were sensitive to inhibition of RNA synthesis by seminalplasmin immediately on addition (Fig. 3) also rules out decreased permeability as an explanation for the lysis resistance of these mutants.

Resistance of these temperature-sensitive, autolysis-defective mutants to lysis induced by seminalplasmin at 37 or 42 °C but not at 30 °C provides strong evidence for our hypothesis that seminalplasmin, like penicillin, lyases E. coli by activating autolysis (Chitnis et al., 1987). However, seminalplasmin-induced lysis differs from that of penicillin in that it does not require continued protein or RNA synthesis (Chitnis et al., 1987). Further, the fact that the mutants were sensitive to inhibition of RNA synthesis by seminalplasmin supports our earlier observation (Chitnis et al., 1987) which indicated that the RNA-synthesis-inhibitory activity of seminalplasmin was independent of its lytic activity.

Mechanism of autolysis deficiency in the mutants

The mutants described here were resistant to lysis induced by the various antibiotics only at the nonpermissive temperature, the temperature at which they failed to grow. Since non-growing cells autolyse poorly (Leduc et al., 1982), there exists the possibility that the defective autolysis in these mutants is merely due to their defective growth as a result of mutation in an essential gene (not involved in autolysis). This trivial explanation is, we think, unlikely because the mutants were resistant to lysis induced by seminalplasmin, which lyses non-growing cells such as cells treated with chloramphenicol or rifamycin (Chitnis et al., 1987). We therefore believe that the mutations are in a gene or genes involved in autolysis, and defective autolysis leads to impaired growth.

If these mutants are genuine autolysis-defective mutants, as we think they are, then the defect(s) may lie either in a gene(s) for an autolysin or in a gene(s) involved in regulation of the autolysin activity. We think it unlikely that the mutation(s) is in the gene for an autolysin because the lysis resistance was suppressed in relA strains (Fig. 5). It is most likely, therefore, that the mutants are defective in the regulation of autolysis.

According to Kusser & Ishiguro (1987), the mutants of Shimmin et al. (1984) were defective in autolysis because they exhibited the stringent response even without starvation for amino acids. This conclusion was based on the following observations: (1) the mutants showed the stringent response at the nonpermissive temperature only, that is, at the temperature at which they were
resistant to antibiotic-induced lysis; (2) autolysis is known to be inhibited under a stringent response (Kusser & Ishiguro, 1985); and (3) the lysis-resistant phenotype of the mutants was suppressed in a relA background or on addition of stringent-response inhibitors. Kusser & Ishiguro (1987) further hypothesized that the loci lytA and lytB identified by their mutants interact directly or indirectly with relA to prevent its activation under non-starvation conditions.

The above model is, however, inadequate to explain the behaviour of our mutants. If the function of the lyt-1 product is only to keep the relA product under control (preventing the stringent response under non-starvation conditions), one would expect relA lyt-1 strains to be temperature-resistant. However, the relA lyt-1 strain CCMB1008 was temperature-sensitive, suggesting that the lyt-1 product has a role in bacterial growth independent of relA. The relA lyt-1 strain (CCMB1008), although more sensitive to antibiotic-induced lysis than the isogenic relA+ lyt-1 strain, was much less sensitive to antibiotic-induced lysis than the relA lyt-1+ strain, NF162 (Fig. 5). This partial suppression of lyt-1 by relA suggests that lyt-1 has a role in the regulation of autolysis independent of any role it may have through relA, and that antibiotic-induced autolysis in E. coli may have at least two pathways that differ in their regulation.

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References


