The Formation of a Dissociable Plasmid Cointegrate from the Flac Factor and the Resident Plasmid of Salmonella typhimurium LT2

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SUMMARY

The Flac factor showed unstable maintenance in Salmonella typhimurium dnaC MP10LT2. The properties of a more stable lac+ derivative (SD-I) are described. SD-I was ts and carried the fi+ property and the ability to transfer the lac+ character. It contained a large plasmid of molecular weight about \(1.29 \times 10^6\) daltons. The properties of SD-I and its derivatives suggested that the large plasmid was a cointegrate of Flac and the MP10LT2 plasmid. Lac+ transfer was efficient from SD-I to M799 MP10LT2 and one lac+ exconjugant contained the intact cointegrate. The cointegrate was not successfully transferred to strains lacking MP10LT2. It dissociated into apparently unaltered Flac and MP10LT2 plasmids, but the deletion of small parts of one or both plasmids during cointegrate formation could not be ruled out. Cointegrate dissociation was more marked in M799 than in SD-I especially during growth in glucose-Casamino acids minimal medium. In the presence of R1drd19, the cointegrate (like the MP10LT2 plasmid) was stably maintained in the dnaC strain; maintenance of Flac was, however, unstable. It seems likely that replication of the cointegrate was controlled by the MP10LT2 plasmid constituent.

INTRODUCTION

During previous work on plasmid replication in dnaC and dnaC+ strains of Salmonella typhimurium, it was observed (Rodriguez Lemoine & Rowbury, 1975b) that whereas Flac was stably maintained in the dnaC+ strains at all the temperatures tested, maintenance of Flac was aberrant at permissive temperatures in the temperature-sensitive dnaC mutant. After overnight growth in broth at 32 °C, 90% of organisms were lac-. Unstable maintenance was dependent on the presence of the resident plasmid as well as on the dnaC lesion. Stably lac+ derivatives can be isolated from this strain and we describe the properties of one such derivative.

The resident plasmid MP10LT2 (previously called the LT2 plasmid) is a large stringently controlled plasmid of molecular weight about \(6.0 \times 10^6\) daltons (Spratt, 1972; Spratt, Rowbury & Meynell, 1973; Smith et al., 1973). The plasmid, which is apparently non-transferable, is stably maintained, but cured strains (which lack the fi+ property conferred by it) have been isolated and studied (Smith et al., 1973; Spratt et al., 1973). Macrina & Balbinder (1972) isolated a large plasmid (FlacS) from a F\(_{1\text{gal}}\)lac derivative of S. typhimurium. FlacS showed certain properties characteristic of MP10LT2 (Macrina & Balbinder, 1973; Rodriguez Lemoine & Rowbury, 1975a). Nevertheless, the failure of FlacS DNA to hybridize with that of the MP10LT2 plasmid led Macrina, Balbinder & Bassel (1973) to conclude that FlacS might not be a hybrid of F\(_{1\text{gal}}\)lac and MP10LT2. In this paper, we describe...
the formation of a large plasmid in *S. typhimurium* IIG dnaC Flac MP10LT2. This plasmid is apparently a cointegrate of Flac and the MP10LT2 plasmid, since it conferred properties characteristic of both and dissociated into apparently unaltered Flac and MP10LT2 plasmids. Transfer of the cointegrate of Flac and the MP10LT2 plasmid was studied, since it provided a possible means of transferring MP10LT2. Maintenance of the cointegrate was also examined in the presence of another plasmid to ascertain which component governed replication.

**METHODS**

**Bacteria.** *Salmonella typhimurium* strains IIG, IIG MP10LT2, IIG MP10LT2 Flac, IIG FlacS, PG154 MP10LT2 Flac, M827 and M799 MP10LT2 have been described previously (Spratt *et al.*, 1973; Rodriguez Lemoine & Rowbury, 1975b). Strain M799 FlacS was derived from strain M799 MP10LT2 by transfer of FlacS. *Escherichia coli* strain c600 is a K12 derivative and requires threonine, leucine and thiamin for growth.

**Culture media.** The minimal medium (MM) used was that of Davis & Mingioli (1950). Citrate was omitted and glucose or lactose (0.2%) was added as energy source. Required amino acids were added at 20 μg ml⁻¹ (l form), thiamin at 1 μg ml⁻¹ and Difco vitamin-free Casamino acids at 0.1%. Oxoid nutrient broth no. 2 was used as a rich liquid medium. MM and broth were solidified where necessary with 2% (w/v) Difco Bacto agar. To detect lac⁺ and lac⁻ colonies, lactose–deoxycholate (DOC) agar (Meynell & Meynell, 1970) was used.

**Viable counts.** The number of viable cells in cultures was measured by plating samples (suitably diluted in 0.065 M-phosphate buffer pH 7.4) on nutrient agar or lactose–DOC agar, and counting colonies after 2 days incubation at 25 °C or 30 °C.

**Tests for sensitivity to MS2 phage.** Two methods were used: (i) 0.1 ml portions of cultures grown overnight in broth were spread on nutrient agar plates and drops of MS2 phage [0.02 ml; 10⁸ plaque-forming units (p.f.u.)/ml] were transferred on to marked areas of the plates; (ii) 0.1 ml portions of cultures grown overnight in broth were added to 2.5 ml soft agar (nutrient broth containing 0.8% Difco Bacto agar and 0.8% NaCl) and poured on to nutrient agar plates. After setting, drops of MS2 phage (about 0.02 ml; 10⁸ p.f.u./ml) were transferred on to marked areas of the plates. After incubation overnight at 30 °C or 37 °C, MS2 sensitive strains showed clear areas where the phage had been placed.

**Transfer of lac⁺ character by conjugation.** Donor strains were grown to late-exponential phase in broth without shaking at the appropriate temperature. Recipient strains were grown to exponential phase in broth with shaking. Recipient cells (0.1 ml of a suitable dilution) were spread on lactose minimal agar plates containing the growth requirements of the recipient. Drops of donor culture [appropriately diluted in 0.85% (w/v) NaCl] were then transferred on to marked areas of the plates. *Lac⁺* exconjugants were picked after 72 h at 30 °C or 48 h at 37 °C.

**Analysis of plasmid DNA.** The growth, labelling and lysis of cells, separation of plasmid DNA on alkaline sucrose gradients, and analysis of gradients were all performed as described previously (Spratt *et al.*, 1973; Rodriguez Lemoine & Rowbury, 1975a). The molecular weights of plasmids were estimated from their sedimentation behaviour on alkaline sucrose gradients (Clayton & Vinograd, 1967).

**Experiments with Rdrdr19.** This R factor was transferred from *Escherichia coli* 153 as described previously (Rodriguez Lemoine & Rowbury, 1975a). R⁺ organisms were selected by plating on minimal agar supplemented with the growth requirements of the recipient and with kanamycin (25 μg ml⁻¹) and chloramphenicol (25 μg ml⁻¹). Where strains carrying
A dissociable plasmid cointegrate

Fig. 1. Analysis of the plasmid content of the stably lac+ derivative (sd-1) by alkaline sucrose gradient centrifugation. Strains 11G MP1079 Flac and sd-1 were labelled with [3H]thymidine in lactose-Casamino acids MM. Lysis of the organisms, sedimentation of gradients, gradient analysis and counting procedures were as described in Methods. In all figures, fraction 1 corresponds to the bottom of the gradient tube. (a) sd-1; (b) strain 11G MP1079 Flac.

Fig. 2. Sedimentation on an alkaline sucrose gradient of the sd-1 plasmid and FlacS. sd-1 was grown and labelled with [3H]thymidine as described in Fig. 1. Strain 11G FlacS was grown and labelled as described in Fig. 1, but using [14C]thymidine (4 µCi ml⁻¹) instead of [3H]thymidine. The two suspensions were then mixed and lysed together. Lysis, sedimentation and all further analytical procedures were as described in Methods. (a) 14C counts, i.e. plasmid content of strain 11G FlacS; (b) 3H counts, i.e. plasmid content of sd-1.

R1drd19 were tested for the number of R⁺ organisms, plating was on nutrient agar with the same concentrations of kanamycin and chloramphenicol.

RESULTS

A large plasmid in a derivative of Salmonella typhimurium 11G

When S. typhimurium 11G dnaC MP1079 Flac (parent) was plated on lactose–deoxycholate agar at 25 °C, many of the organisms formed white colonies with red centres, i.e lac+ maintenance was unstable. About 0.5% of the organisms, however, formed red stably lac+ colonies. One of these stably lac+ derivatives (sd-1) was purified and studied.

sd-1 was, like its parent, ts and was able to transfer the lac+ character to strain M799 MP1079. sd-1 was, moreover, resistant to MS2 phage and therefore carried characteristics of both Flac (lac+ character and transfer ability) and the MP1079 plasmid (fi⁺ character).

The plasmid DNA content of sd-1 was compared with that of its parent by running extracts on alkaline sucrose gradients. The extract prepared from the parental culture showed the two peaks characteristic of the covalently closed circular (CCC) forms of Flac (about 1.65% of the total cellular DNA as CCC plasmid) and the MP1079 plasmid (about 1.9% of the total cellular DNA as CCC plasmid). However, extracts of sd-1 cultures contained substantial amounts (about 3.6% of the total cellular DNA as CCC plasmid) of a...
Fig. 3. Analysis of the plasmid content of a lac− segregant of sd-1 by alkaline sucrose gradient centrifugation. Organisms of a lac− segregant from sd-1 were labelled with [3H]thymidine in glucose-Casamino acids MM. Strain PG154 MP10LTZ Flac was labelled with [14C]thymidine in lactose-Casamino acids MM. Cell suspensions were then mixed and lysed together. All subsequent procedures were as described in Methods. (a) 14C counts, i.e. plasmid content of strain PG154 MP10LTZ Flac; (b) 3H counts, i.e. plasmid content of the lac− segregant from sd-1.

Fig. 4. Analysis of the plasmid content of a lac+ exconjugant from a cross of sd-1 × MPG9 MP10LTZ by alkaline sucrose gradient centrifugation. The exconjugant was grown in lactose-Casamino acids MM and labelled with [3H]thymidine as described in Fig. 1. Sedimentation, analysis of gradients and counting of samples were also performed as in Fig. 1.

large plasmid (Fig. 1), as well as smaller amounts of plasmids which behaved like Flac (about 0.35% of the total cellular DNA) and the MP10LTZ plasmid (about 0.36% of the total cellular DNA).

The large sd-1 plasmid was larger (Fig. 2) than the hybrid FlacS factor (molecular weight about 109 × 10^6 daltons; Macrina et al., 1973) and its molecular weight was estimated to be 128 × 10^6 to 130 × 10^6 daltons. It seemed likely that the sd-1 plasmid was a cointegrate of Flac and the MP10LTZ plasmid, since sd-1 had properties characteristic of both. The molecular weight estimated was somewhat less than that expected for a cointegrate made by fusion of the complete genomes of Flac (molecular weight about 80 × 10^6 daltons) and the MP10LTZ plasmid (molecular weight about 60 × 10^6 daltons). Some DNA might therefore have been deleted in the fusion.

The small amounts of apparently normal Flac and MP10LTZ plasmids present in sd-1 extracts might have arisen by dissociation of a cointegrate. Dissociation would result in the presence of two types of derivative in sd-1 cultures. Organisms carrying the two constituent plasmids would arise directly; lac+ maintenance should be unstable in them. From these, lac− organisms carrying only the MP10LTZ plasmid should arise. When broth-grown cultures of sd-1 were plated on lactose-deoxycholate agar at 25 °C, 5 to 6% of the organisms formed white colonies with red centres, i.e. maintenance of the lac+ character was unstable in them (Table 1). Organisms from one of these colonies contained plasmids which behaved like
Fig. 5. Comparison of the derived Flac with the parental Flac by sedimentation on an alkaline sucrose gradient. Organisms of strain m827 carrying the derived Flac (see Table I) and strain PG154 MP10L7E Flac were labelled with [H] and [3C]thymidine respectively in lactose-Casamino acids MM. Organisms were lysed together and treated subsequently as in Fig. 2. (a) 14C counts, i.e. plasmid content of PG154 MP10L7E Flac; (b) 3H counts, i.e. plasmid content of m827 derived Flac.

Flac and the MP10L7E plasmid on alkaline sucrose gradients, but the large plasmid was absent. A further 2 to 3% of the organisms from a SD-I culture formed white (lac-) colonies on lactose-deoxycholate agar. All three of these tested (e.g. Fig. 3) contained only a plasmid which behaved like MP10L7E.

Transfer properties of SD-I

As stated above, SD-I transferred the lac+ character when incubated with strains such as m799 MP10L7E. However, 5 to 6% of the organisms in a SD-I culture (those showing unstable lac+ maintenance) probably carried Flac and these might have been responsible for all the lac+ transfer. Quantitative measurements rule this out. Transfer of the lac+ character to m799 MP10L7E was somewhat more efficient from SD-I (2.9 x 10^-4 lac+ exconjugants per donor organism) than from IG MP10L7E Flac (2.4 x 10^-4 lac+ exconjugants per donor organism). It follows that organisms carrying the cointegrate were responsible for most of the lac+ transfer.

Extracts from one lac+ exconjugant from the cross of SD-I x M799 MP10L7E contained the plasmid cointegrate (Fig. 4). Dissociation of the cointegrate was more extensive in strain m799 since substantial amounts of plasmids which behaved like Flac and MP10L7E were also present (Fig. 4). Growth of the m799 derivative in glucose medium rather than lactose led to even further dissociation (about 1% of total DNA as CCC form of the SD-I plasmid in glucose-Casamino acids MM, but about 3% in lactose-Casamino acids MM).

Attempts to transfer the cointegrate into strains lacking MP10L7E were unsuccessful. Very few lac+ exconjugants arose when SD-I was crossed with m827 and these probably received only Flac since 45/45 were MS2 sensitive (i.e. lacked the fi+ property characteristic of MP10L7E and the cointegrate) and extracts from one contained only a single plasmid which sedimented like Flac on alkaline sucrose gradients. Similarly, after a cross of m799 containing the cointegrate with IG, the three lac+ exconjugants tested were MS2 sensitive and one of them contained a single plasmid which behaved like Flac on alkaline sucrose gradients. When E. coli C600 was used as recipient in crosses with SD-I or the m799 derivative carrying the cointegrate, no lac+ exconjugants were isolated.

Properties of the plasmids deriving from dissociation of the SD-I plasmid

The large plasmid of SD-I evidently arose by fusion of Flac and MP10L7E. Its molecular weight, however, appeared to be somewhat less than the sum of the molecular weights of

8-2
Table 1. Plasmid stability in derivatives of Salmonella typhimurium strain IIG

Flac was transferred into the IIG derivatives from m827 Flac. The derived Flac originated in an unstable lac+ derivative of SD-I. From there it was transferred to m827 and thence to the appropriate IIG derivatives. The strain IIG derivative carrying the derived MPIoLTZ plasmid was a lac- segregant from SD-I. Organisms were taken from slopes of supplemented minimal agar plus lactose and grown overnight in broth at 30 °C. Results are expressed as percentages.

<table>
<thead>
<tr>
<th>Strain</th>
<th>lac- cells</th>
<th>Unstably lac+ cells</th>
<th>Stably lac+ cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>IIG Flac</td>
<td>0.6</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>IIG derived Flac</td>
<td>2.0</td>
<td>NT</td>
<td>NT</td>
</tr>
<tr>
<td>SD-I</td>
<td>2.3</td>
<td>6.6</td>
<td>91.1</td>
</tr>
<tr>
<td>IIG MPIoLTZ Flac</td>
<td>80.0</td>
<td>19.7</td>
<td>0.3</td>
</tr>
<tr>
<td>IIG MPIoLTZ derived Flac</td>
<td>71.4</td>
<td>28.4</td>
<td>0.2</td>
</tr>
<tr>
<td>IIG Flac derived MPIoLTZ</td>
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<td>21.7</td>
<td>0.3</td>
</tr>
<tr>
<td>IIG derived MPIoLTZ derived Flac</td>
<td>80.1</td>
<td>19.4</td>
<td>0.5</td>
</tr>
</tbody>
</table>

NT, not tested.

the constituents. It may be that the molecular weight of large plasmids is somewhat underestimated by measurements of sedimentation in alkaline sucrose. It was possible, however, that the SD-I plasmid lacked parts of one or both constituents, as seems likely for the FlacS plasmid. Accordingly we have compared the sizes and properties of the plasmids (derived Flac and derived MPIoLTZ) formed by dissociation of the cointegrate with those of the parental Flac and MPIoLTZ plasmids. The derived Flac co-sedimented with the parental plasmid on an alkaline sucrose gradient (Fig. 5) indicating that it was essentially unchanged in size. Transfer of the derived Flac (1.1 x 10^-2 lac+ exconjugants per donor organism in a cross of m827 derived Flac x IIG MPIoLTZ) was as efficient as that of the parental Flac (1.0 x 10^-2 lac+ exconjugants per donor organism in a cross of m827 Flac x IIG MPIoLTZ) and the derived Flac retained sensitivity to repression of its transfer properties by the fi+ MPIoLTZ plasmid. The derived Flac also behaved like the parental Flac in strain IIG MPIoLTZ. Maintenance of both was unstable and stably lac+ derivatives arose with approximately equal frequencies (Table 1). In a derivative of strain IIG lacking MPIoLTZ, both the derived Flac and the parental form were stably maintained (Table 1). The derived MPIoLTZ plasmid co-sedimented with the parental form on an alkaline sucrose gradient (Fig. 3). Furthermore it conferred on strain IIG the fi+ property characteristic of the parental MPIoLTZ plasmid. The derived MPIoLTZ plasmid showed unchanged behaviour in strain IIG Flac. Its presence caused unstable maintenance of Flac and stably lac+ derivatives arose with a frequency similar to that observed with IIG Flac carrying the parental MPIoLTZ plasmid (Table 1).

The derived MPIoLTZ plasmid also retained the characteristic compatibility properties of the parental plasmid. Like the parental plasmid (Rodriguez Lemoine & Rowbury, 1975a), it was incompatible with the hybrid FlacS as shown by the observation that introduction of FlacS into a lac- segregant derived from SD-I caused the loss of MPIoLTZ.

Control of cointegrate replication; replication in the presence of R1drr19

Unstable maintenance of Flac in the dnaC strain was not only caused by the MPIoLTZ plasmid. Flac maintenance was also unstable (Rodriguez Lemoine & Rowbury, 1976) in the presence of R factors like R1drr19 (61% of organisms were lac-) after overnight growth of S. typhimurium dnaC Flac R1drr19 in broth at 30 °C; 100% were R+), whereas the MPIoLTZ plasmid was stably maintained with R1drr19 (51/51 organisms tested were
A dissociable plasmid cointegrate

MP10LT2 R+ after overnight growth of *S. typhimurium dnaC* MP10LT2 R1drt9 in broth at 30 °C. When R1drt9 was introduced into SD-1, the strain remained stably lac+ (2.5% of organisms were lac- after overnight growth of SD-1 in broth at 30 °C; 2.7% were lac- after overnight growth of SD-1 R1drt9 in broth at 30 °C). It follows that the cointegrate behaved as though its replication could be under the control of the LT2 plasmid constituent.

DISCUSSION

Flac was not stably maintained in the presence of the MP10LT2 plasmid in *S. typhimurium* strain I1G, but stably lac+ derivatives could arise in a number of ways (Rodriguez Lemoine & Rowbury, 1975b). The stably lac+ character of SD-1 clearly derived from the presence of a single plasmid cointegrate; single plasmids can be stably maintained in strain I1G (Rodriguez Lemoine & Rowbury, 1975b; unpublished observations). The following observations support the conclusion that the cointegrate was formed by fusion of Flac and the MP10LT2 plasmid: (i) the presence of the cointegrate in SD-1 was associated with substantially reduced amounts of Flac and the MP10LT2 plasmid (Fig. 1); (ii) some organisms in SD-1 cultures carried both Flac and the MP10LT2 plasmid and the cointegrate was absent from them.

The presence of Flac and MP10LT2 in extracts from SD-1 cultures (Fig. 1) suggested that the cointegrate was dissociable. The isolation of a derivative containing both Flac and MP10LT2 from SD-1 reinforced this view. The extent of dissociation was apparently increased in strain M799, especially when organisms were grown with glucose rather than lactose.

The Flac and MP10LT2 plasmids which derived from the cointegrate were not significantly altered compared to the parental plasmids with respect to molecular weight or other properties tested. This supports the view that the cointegrate contains essentially the complete genomes of the two constituents. In contrast, there was a marked discrepancy between the observed molecular weight of the cointegrate and that expected for a hybrid produced by fusion of the complete genomes of Flac and MP10LT2. It may be therefore that the cointegrate lacks a small part of one or both constituents. Studies of the cointegrate by restriction endonuclease ‘fingerprinting’ or by electron microscopy will be necessary to resolve this problem. If the SD-1 plasmid does carry a deletion then this might be responsible for the failure to transfer the cointegrate to strains lacking MP10LT2.

Transferable cointegrates which have a tendency to dissociate may be useful for transferring otherwise non-transferable plasmids. The MP10LT2 plasmid has not so far been transferred as a separate unit but transfer of the SD-1 cointegrate (Fig. 4) may eventually permit establishment of the MP10LT2 plasmid in strains lacking it.

Where plasmid hybrids are formed by the fusion of parts or the whole of two constituent plasmids then the hybrid may potentially have two distinct replication systems. Some such hybrids can apparently utilize either replication system, e.g. the replication of the hybrid pSCI34 is governed by the ColE1 constituent in the presence of chloramphenicol but by the pSCI10 constituent in polA mutants (Timmis, Cabello & Cohen, 1974). The SD-1 cointegrate described here clearly contains the replication system of both constituents, since both plasmids derived from the cointegrate were able to replicate in the absence of other plasmids. In the presence of R1drt9, replication of the cointegrate appeared to be under the control of the MP10LT2 plasmid constituent in strain I1G since the cointegrate, like this plasmid, was stably maintained. If the cointegrate is under the control of the MP10LT2 plasmid constituent in SD-1 itself then we would expect very stable maintenance since the MP10LT2
plasmid and FlacS are very rarely lost from strain 11G MP10LT2 or strain 11G FlacS (Rodriguez Lemoine & Rowbury, 1975b). So far we have found no lac- segregants of SD-1 which have lost the complete cointegrate; all lac- segregants tested carried the MP10LT2 plasmid and therefore arose by dissociation of the cointegrate rather than by its loss. We are further examining the replication of the cointegrate to ascertain whether the F factor constituent can govern replication under suitable conditions.

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