JOURNAL OF BACTERIOLOGY, Mar. 1985, p. 1080–1085
0021-9193/85/031080-06$02.00/0
Copyright © 1985, American Society for Microbiology
Vol. 161, No. 3

Efficiency of Induction of Prophage λ Mutants as a Function of *recA* Alleles

M. DUTREIX, A. BAILONE, AND R. DEVORET*

Section de Radiobiologie Cellulaire, Laboratoire d'Enzymologie, Centre National de la Recherche Scientifique, F-91190 Gif-sur-Yvette, France

Received 6 June 1984/Accepted 30 November 1984

Mutants of the *c*I gene of prophage λ have been defined phenotypically in a *recA*$^+$ host as noninducible (Ind$^-$), inducible (Ind$^+$), or induction sensitive (Ind^s). We showed that a phage λ *c*I$^+$ carrying operator mutations *v*2 and *v*3 displays an Ind^s phenotype, as does λ *c*I *ind*^{s}-1. We characterized a fourth induction phenotype called induction resistant (Ind^r). Using these four prophage types, we tested the influence of bacterial *recA* mutations on prophage induction. Ind^r prophages were fully induced in *recA441* bacteria whose RecA441 protein is activated constitutively. Ind^r prophages were not induced in a mutant overproducing RecA$^+$ protein, confirming that RecA$^+$ protein must be activated to promote prophage induction. Ind^s prophages were induced in *recA142* and *recA453-441* lysogens, previously described as deficient in prophage induction.

Induction of prophage λ results from cleavage of the *c*I repressor (for a review, see reference 31). Cleavage has been observed with two other phage repressors, P22 and 434, and with LexA protein, the cellular repressor of SOS genes. In each case the cut occurs between alanine and glycine, in comparable positions in the four polypeptides. The cleavage site in λ *c*I repressor is located in a hinge region between two domains—the amino terminal binding to the operator and the carboxy terminal binding to repressor monomers (27, 34).

It has recently been shown by Little (20) that LexA and λ *c*I proteins autodigest in vitro. Yet, in vivo RecA protein is required in the cleavage reaction. To reexamine the relationship between phage repressor and RecA protein, we determined how prophage λ *c*I and bacterial *recA* mutations affect the efficiency of lysogenic induction.

Two λ *c*I mutations alter repressor inactivation: (i) *ind*^{s}-1 affects λ repressor in such a way that it is cleaved 5- to 10-fold faster than wild-type λ *c*I$^+$ repressor (7); (ii) *c*I *ind*1, located near the site of cleavage (19), prevents λ repressor inactivation (33). We found a novel phenotype, called induction resistant (Ind^r) among a set of *c*I mutants isolated by Eshima et al. (10). Prophage λ can display the following four induction phenotypes, in order of decreasing inducibility: Ind^s > Ind$^+$ > Ind^r > Ind$^-$.

Using the four prophage induction phenotypes, we characterized the efficiency of induction of various *recA* mutants so as to estimate the cleavage facilitation by a mutated RecA protein. Four types of *recA* mutants can be recognized that can be classed in the following order of RecA-promoting prophage induction: RecA (Ind$^-$) < RecA (Ind$^\pm$) < RecA (Ind$^+$) < RecA (Ind^{++}).

The RecA (Ind$^\pm$) phenotype is illustrated by two mutants, *recA142* and *recA453-441*, in which Ind^s prophages can be fully induced. The first mutant may have a defect in activation because of a defective interaction of RecA142 protein with DNA and ATP (32), and the second mutant is probably a down-promoter mutant (22) since the basal level of RecA protein is reduced (30).

Figure 1 summarizes the currently accepted mechanisms that determine the efficiency of prophage induction.

* Corresponding author.

MATERIALS AND METHODS

Bacterial strains, phages, cultures, and media. The bacterial strains used are listed in Table 1. Many of them were made lysogenic for prophages described below.

Prophage repressor mutants derived from λ wild-type prophage were λ *c*I *ind*^{s}-1 (17); λ *c*I *ind*553, λ *c*I *ind*502, and λ *c*I *ind*543 (10); and λ *c*I857 ind$^-$. Prophage λGY15 (29) encodes a wild-type *c*I$^+$ repressor and *v*2 and *v*3 operator constitutive mutations.

Stocks of noninducible prophages λ *c*I *ind*502, λ *c*I *ind*543, and λ *c*I *ind*553 were produced by zygotic induction.

Lysogens were isolated as single colonies purified from spots of confluent lysis and tested for immunity by replica-plating on EMBO plates overlaid with 10^9 homoimmune *c*I$^-$ phages (14). Single lysogens were identified by their sensitivity to weak virulent phage λ *c*I90 *c*Y17 (2). Monolysogens were also differentiated from dilysogens carrying two prophages in tandem by the low efficiency of prophage excision after superinfection with phage λ *imm*434 *c*I$^-$ *int*102 (14, 18).

Bacteria were grown in LBT medium (9) or in synthetic medium YM9C (8). Colonies were scored on LAT medium (9). GT or GT-ampicillin plates, supplemented with 15 μg of ampicillin per ml, were used for plating infective centers (23). TMG dilution buffer contained 10 mM $MgSO_4$, 10 mM Tris-hydrochloride (pH 7), and 0.1% (wt/vol) gelatin. All cultures and plates were incubated at 37°C unless otherwise stated.

Measurement of prophage induction. The induced infective centers were scored on GT-ampicillin plates to reduce the background of spontaneous phage production. To score infective centers from poorly inducible lysogens, we reduced the amount of GY4925 indicator bacteria. The efficiency of prophage induction is estimated by the proportion of infective centers formed by the lysogens. Free phage were measured after killing of the lysogens by chloroform. Clear plaque mutants were scored on GT plates.

UV irradiation. Samples (2 ml) of bacterial suspensions in TMG were irradiated in 5-cm petri dishes with a 15-W General Electric lamp (254 nm). UV doses were measured with a Latarjet dosimeter.

Tif induction. *recA441* (Tif) bacteria, grown at 32°C in YM9C, were shifted to 42°C by a fourfold dilution in

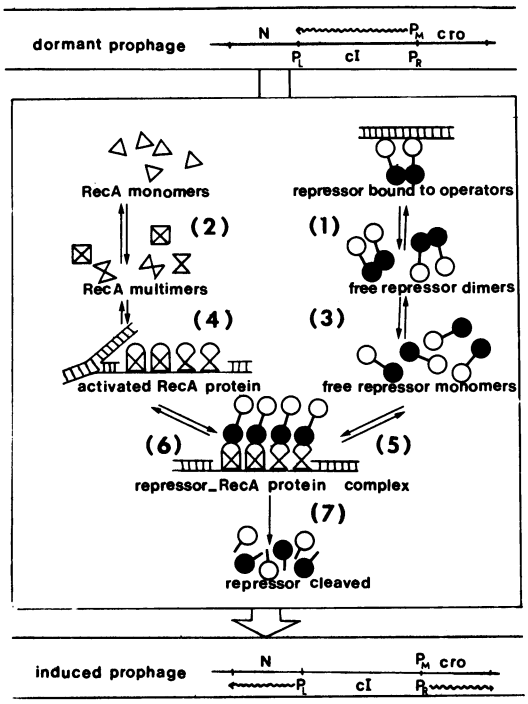

FIG. 1. Regulation of lysogenic induction. The current scenario for prophage λ derepression is represented as follows. In a lysogen, in which λ repressor concentration is constant (4, 15), the prophage remains dormant because repressor dimers are bound to operators (reaction 1). There is an equilibrium between monomers and dimers (reaction 3). RecA protein forms multimers (reaction 2) (30). After treatment of the lysogens by inducing agents, RecA protein is activated (24) in a ternary complex (reaction 4) that interacts with repressor monomers (reactions 5 and 6) (28). Cleavage of repressor monomers starts (reaction 7). Since the concentration of repressor monomers is decreasing, repressor dimers tend to dissociate into monomers that are subject to cleavage. When the concentration of dimers is 10-fold lower than normal, repression is no longer maintained, and phage growth ensues (4). Here are listed *cI* and *recA* alleles that may alter the following reactions. Odd or even numbers are used, respectively, to designate phage or RecA reactions. Reactions: 1, prophage λGY15 (this paper); 3, λ *cI ind*^{s}-1 (7), λ *cI ind*502, and λ *cI ind*543 (this paper); 5, phage 21 and LexA repressors, which interact with RecA protein differently from λ repressor (9); 2, *recAo98* (29) and *recA453* (30); 4, *recA441* (35) and *recA142* (32); 6, *recA430* (9); 7, λ *cI ind*553 (this paper) and λ *cI ind*1 (33).

prewarmed YM9C supplemented with 100 μg of adenine per ml and incubated further (5).

RESULTS

New induction phenotype displayed by phage λ *cI ind*543. Phages λ *cI ind*543 and λ *cI ind*553 were isolated and characterized as noninducible by Eshima et al. (10). We found that prophage λ *cI ind*543 was induced in about 10% of *recA*$^+$ lysogens at a UV dose of 40 J/m^2 (Fig. 2); the resulting burst size was more than 100 phage per cell after incubation for 150 min (Fig. 3). In contrast, prophage λ *cI ind*553 behaved like the classical noninducible prophage λ *cI ind*1, giving rise to 10^{-6} infective centers per lysogen.

Upon Tif induction, GY5261 *recA441* (λ *cI ind*543) lysogens lysed between 90 and 165 min, whereas GY5260 *recA441* (λ) lysogens lysed between 60 and 120 min (Fig. 4). The delayed lysis of GY5261 may result from a slow rate of cleavage of λ *cI ind*543 repressor. Lysogens for λ *cI ind*553 grew normally and released about 10^2 free phage per ml, confirming that phage λ *cI ind*553 was noninducible (Fig. 4).

Under conditions that inhibit Tif induction (12)—bacterial growth in rich medium at 32°C—the efficiency of induction of GY5261 *recA441* (λ *cI ind*543) lysogens by UV light was 10%, as was also observed in GY5257 *recA*$^+$ (λ *cI ind*543) (Fig. 2; data not shown).

Next, we asked whether prophage λ *cI ind*543 would be more efficiently induced in DM1187 *lexA51* (Def) *recA441*, in which RecA441 protein is amplified by the inactivation of the LexA repressor by mutation *lexA51* (Def) (21). DM1187 can be lysogenized by phage λ *cI ind*1, whose repressor is resistant to cleavage, but not by phage λ (26). DM1187 bacteria were lysogenized with phage λ *cI ind*543 at 32°C, giving rise to GY5262 *lexA51* (Def) *recA441* (λ *cI ind*543), which released phage spontaneously at a high level, about 20% of the cell titer (Fig. 4). Upon Tif induction, GY5262 lysogens lyzed massively, 90 min earlier than did GY5261 *lexA*$^+$ *recA441* lysogens (Fig. 4), indicating that a high basal level of RecA441 protein shortened the latent period of prophage λ *cI ind*543 induction.

Note that an 11-fold increase in the basal cellular level of RecA protein by a *recAo98* operator mutation (13, 29) was nevertheless insufficient to efficiently induce GY5249 *recAo98* (λ *cI ind*543) by UV light (10% induction at most; data not shown). This fact confirms previous findings that RecA$^+$ protein must be activated to promote prophage induction.

The phenotype of prophage λ *cI ind*543 was called induction resistant (Ind^r). Prophage λ *cI ind*502 (10) also exhibited an Ind^r phenotype (data not shown). The two mutations *ind*543 and *ind*502 have been located by genetic recombination in the A region of *cI* (10), which encodes the carboxy-terminal domain of the repressor (19). The observed Ind^r phenotype of prophages λ *cI ind*543 and λ *cI ind*502 might result from an increased tendency of their repressor monomers to form dimers.

The λ *cI ind*543 repressor molecules from cell crude extracts bound operator DNA 1.7-fold and 2.8-fold tighter than λ *cI*$^+$ and λ *cI ind*^{s}-1 repressor molecules (Table 2). The increased binding to operator DNA reducing the availability of cleavable repressor monomers may explain the apparent resistance to cleavage of the *cI ind*543 repressor.

Phage λ *cI*$^+$ *v2 v3* displays an Ind^s phenotype. Prophage λGY15, which carries mutations *v2* in o_{L1} and *v3* in o_{R1} produces virulent mutants by mutation in the o_{R2} operator (3, 16). Since λ *cI* repressor binds poorly to the mutated operators, o_{L1} and o_{R1} (11), we surmised that λGY15 would display an induction-sensitive phenotype.

Indeed, GY5269 *recA*$^+$ (λ *cI*$^+$ *v2 v3*) bacteria were induced at a low UV dose (Fig. 2) as efficiently as were λ *ind*^{s}-1 lysogens and burst out after a 30-min lag, a period 20 min shorter than in UV-induced λ lysogens (Fig. 3).

Prophage induction in *recA142* and *recA453-441* lysogens. The *recA142* and *recA453-441* mutants were described as being deficient in lysogenic induction, (5, 6).

We found that in *recA142* lysogens the efficiency of induction of λ *ind*^{s}-1 and λ *cI*$^+$ *v2 v3* were, respectively, 100 and 20% at a dose of 2 J/m^2 of UV light (Fig. 5). Phage λ *ind*^{s}-1 burst out after a 60-min lag period with a yield of about 100 phage per cell (Fig. 3).

We then reexamined the induction pattern of GY5278 *recA142* (λ) lysogens, which were induced by UV irradiation with an efficiency 10-fold lower than that observed in a *recA*$^+$ lysogen (Fig. 5); spontaneous phage production was

TABLE 1. Bacterial strains

Strain	Relevant genotype			Prophage[a]	Origin or Source
	recA	*lexA*	Other		
AB1157	+	+			Howard-Flanders: GY752
DM455	99	+			Mount (25); GY4677
DM1187	*441*	*51*			Mount (26); GY4627
DM2211	*o98*	+			Ginsburg et al. (13); GY4762
GC3217	*441*	+	*sfiA11*		George et al. (12); GY2813
JC4728	*142*	+			Clark (6) via Roberts; GY4763
JM776	*430*	+			Castellazzi et al.; GY2831
JM1253	*453-441*	+			Castellazzi et al. (5); GY2798
GY4454	+	+		λ (1)	AB1157
GY4909	*430*	+		λ (2)	JM776
GY4925	+	+	*ampA*		Devoret et al. (9)
GY5249	*o98*	+		λcI *ind*543 (1)	DM2211
GY5250	*142*	+		λcI *ind* 543 (1)	JC4728
GY5254	*430*	+		λcI *ind*^{s}-1 (2)	JM776
GY5255	+	+		λcI *ind*^{s}-1 (1)	AB1157
GY5257	+	+		λcI *ind*543 (1)	AB1157
GY5258	*430*	+		λcI *ind*543 (2)	JM776
GY5259	*441*	+	*sfiA11*	λcI *ind*553 (2)	GC3217
GY5260	*441*	+	*sfiA11*	λ	GC3217
GY5261	*441*	+	*sfiA11*	λcI *ind*543	GC3217
GY5262	*441*	*51*	*sfiA11*	λcI *ind*543	DM1187
GY5263	*441*	*51*	*sfiA11*	λcI *ind*553	DM1187
GY5264	+	+		λcI *ind*553 (1)	AB1157
GY5265	*453-441*	+		λ	JM1253
GY5267	*453-441*	+		λcI *ind*^{s}-1	JM1253
GY5269	+	+		λGY15 (1)	AB1157
GY5270	*142*	+		λGY15 (1)	JC4728
GY5273	*453-441*	+		λGY15	JM1253
GY5274	*430*	+		λcI *ind*553 (2)	JM776
GY5278	*142*	+		λ (1)	JC4728
GY5279	*142*	+		λcI *ind*^{s}-1	JC4728
GY6128	*128*	+			Bailone et al. (1)

[a] The number of prophage copies carried by a lysogen is indicated within parentheses. Strains were lysogenized with λ *cI ind*543 or λ *cI ind*502 phages, but only λ *cI ind*543 'ysogens are listed.

also reduced 10-fold. At most 20 phage per cell were released after a long lag period of 90 min and for more than 2 h (Fig. 3), suggesting that phage growth was delayed in UV-damaged *recA142* bacteria. Alteration of phage development in *recA142* lysogens was confirmed by the low burst size of prophage λ *c*I857 after thermal induction. After incubation for 1 h of the UV-irradiated lysogens, the burst size of prophage λ *c*I857 decreased steadily as a function of time (data not shown). Our results indicate that RecA142 protein can be activated in vivo to support repressor cleavage, confirming the data obtained by Roberts and Roberts (32) in vitro.

recA453-441 (λ *c*I$^+$) lysogens were poorly induced by UV light after an extended lag period (Fig. 3 and 5). The two lysogens, *recA453-441* (λ *c*I$^+$ *v*2 *v*3) and *recA453-441* (λ *ind*^{s}-1), were fully induced by UV irradiation (Fig. 3 and 5), but not by Tif induction (data not shown). In contrast, the two Ind^s prophages were not induced at all in other *recA* mutants such as *recA128* (1) and *recA99* (25) (data not shown).

DISCUSSION

To estimate repressor cleavage facilitated by a mutated RecA protein, we characterized the induction of prophage λ by determining quantitatively (i) the efficiency of induction, that is, the percentage of induced cells giving rise to infective centers; (ii) the lag period before phage burst; and (iii) the yield per cell of free phage. The efficiency of prophage induction is often estimated by the sole number of free phage released by induced lysogens. This measurement is rarely meaningful. The frequency of induced cells that rises from a 1% spontaneous background to an induced level close to 100% is mutiplied by 100, the usual burst of phage per cell. If the capacity of the lysogen is normal the ratio of induced phage over the background must be around 10,000.

In this paper, we characterized a new phage induction phenotype, called induction resistant (Ind^r), displayed by two mutants of phage λ, *cI ind*543 and *cI ind*502. The Ind^r phenotype was differentiated from the classical noninducible λ *cI ind*1 by (i) a 10% induction efficiency in wild-type lysogens, (ii) a delayed burst of phage, and (iii) full induction in *lexA51 recA441* lysogen in which the cleavage-promoted activity of RecA441 protein is constitutive (26). Mapping data by recombination establish that mutations *cI ind*543 and *cI ind*502 alter the A region (10) that codes for the corresponding carboxy-terminal domain of the λ repressor (19). The carboxy-terminal domain controls aggregation of monomers to form dimers and the cooperative interaction of dimers in their binding to operators (27).

The observed Ind^r phenotype may result from an increased tendency of λ *cI ind*543 repressor monomers to form dimers. This may entail an enhanced binding of repressor to operators and an increased cellular concentration of the mutant repressor by stimulating transcription from *prm* (34). An Ind^r phage seems to be the opposite of the Ind^s λ *cI ind*^{s}-1 (7). Our assumption is supported by the threefold increase in the operator-binding activity of λ *cI ind*543 repressor.

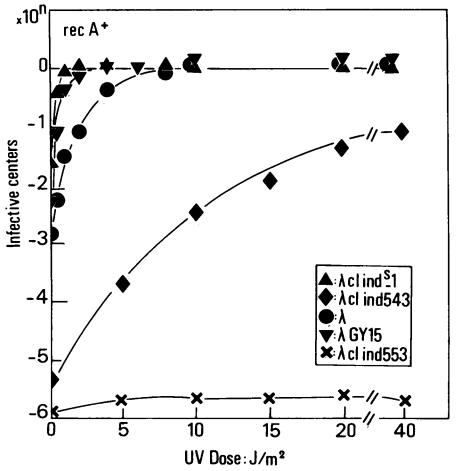

FIG. 2. Four phenotypic prophage induction patterns in a *recA*$^+$ lysogen. Bacteria grown in LBT up to about 10^8 cells per ml were harvested by centrifugation and suspended in TMG buffer. Serial dilutions were exposed to UV light at the doses indicated on the abscissa. The fraction of infective centers to the number of treated cells is plotted on the ordinate. Symbols: GY4454 (●), GY5255 (▲), GY5257 (◆), GY5264 (X), and GY5269 (▼).

The phage called λGY15 displays an Ind^s phenotype, as does λ *cI ind*^{s}-1; (i) it was induced at a low UV dose in a wild-type lysogen, (ii) its latent period of development was shorter than wild type λ, and (iii) it was induced in bacteria such as *recA453-441* and *recA142*, in which wild-type λ is poorly induced. To account for the Ind^s phenotype of λGY15, we postulate that derepression of this prophage can be achieved by the inactivation of a small fraction of repressor molecules, since it carries mutated operators to which the repressor binds poorly (11).

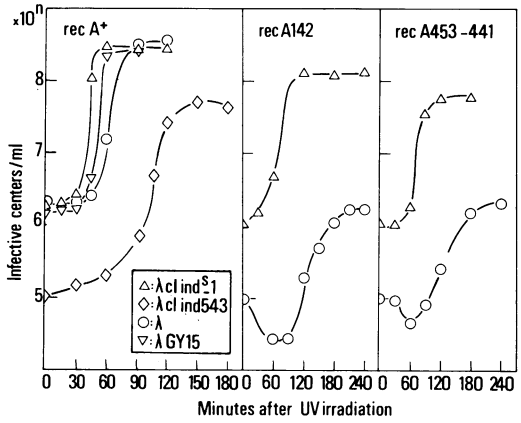

FIG. 3. Phage yields after UV irradiation of *recA*$^+$, *recA142*, and *recA453-441* lysogens. Bacteria grown in LBT medium up to about 10^8 cells per ml were harvested by centrifugation and suspended in TMG buffer. *recA*$^+$ lysogens were exposed to 20 J/m^2, and *recA142* and *recA453-441* lysogens were exposed to 5 J/m^2. Irradiated cells were diluted 1:100 into prewarmed LBT and incubated at 37°C for the time periods indicated on the abscissa. The number of plaques scored on GT-ampicillin plates is plotted on the ordinate. Lysogens: for *recA*$^+$, GY4454 (○), GY5255 (△), GY5257 (◇), and GY5269 (▽); for *recA142*, GY5278 (○) and GY5279 (△); for *recA153-441*, GY5265 (○) and GY5267 (△).

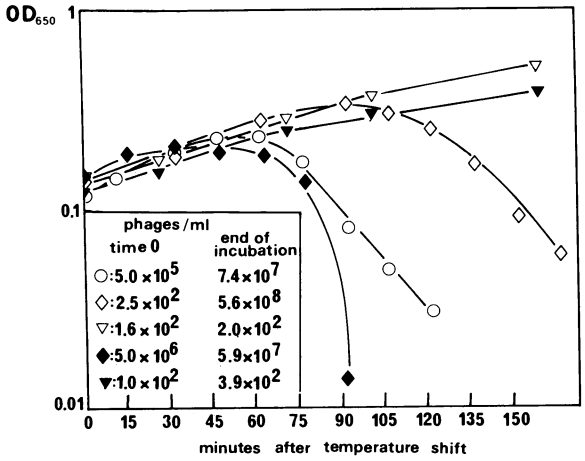

FIG. 4. Cell lysis and free phage production after thermal shift of *recA441* lysogens. Lysogens grown at 32°C in YM9C medium were shifted to 42°C at time 0 by a fourfold dilution into prewarmed YM9C medium supplemented with 100 μg of adenine per ml and incubated further. Prophage induction was monitored by the decrease in optical density at 650 nm (OD_{650}) plotted on the ordinate. Free phage titers indicated in the insert were determined at time 0 and for GY5262 (◆) at 90 min, for GY5260 (○) at 120 min, and for GY5259 (▽), GY5261 (◇), and GY5263 (▼) at 165 min.

The four distinct prophage induction phenotypes can be classed in the order of decreasing inducibility as follows: Ind^s > Ind$^+$ > Ind^r > Ind$^-$.

Using the four types of prophages, we characterized the efficiency of induction of various *recA* mutants so as to estimate the cleavage facilitation by a mutated RecA protein. The following four types of *recA* mutants can be recognized that can be classed in the order of RecA-promoting prophage induction: RecA (Ind$^-$) < RecA (Ind$^\pm$) < RecA (Ind$^+$) < RecA (Ind^{++}).

The RecA (Ind$^+$) phenotype is displayed either by a *recA*$^+$ or a *recAo98* mutant in which Ind^r prophages are poorly induced. The RecA (Ind$^\pm$) phenotype is illustrated by the *recA142* and *recA453-441* mutants, in which Ind^s prophages are fully induced. The first mutant may have a defect in activation of RecA protein because of a defective interaction of RecA142 protein with DNA and ATP (32); the second mutant is probably a down-promoter mutant (22), since the basal level of RecA protein is reduced fivefold and is not amplifiable (30). An explanation for the lack of prophage λ induction in *recA453-441* bacteria is that there is not enough activated RecA441 protein in the cell to support repressor cleavage. The RecA (Ind$^-$) phenotype is displayed by such classical *recA*$^-$ mutants as *recA128* and *recA99*.

The *recA441* mutant displays a RecA (Ind^{++}) or a RecA (Ind$^+$) phenotype according to whether activation of RecA441

TABLE 2. Operator binding activity of mutant repressors in crude cell extracts[a]

Lysogens	Units of repressor
GY4909(λ)	1.3
GY5258(λ *cI ind*543)	2.2
GY5254(λ *cI ind*^{s}-1)	0.8
GY5274(λ *cI ind*553)	1.2

[a] Crude cell extracts and DNA binding assays were performed as described by Levine et al. (18). Repressor activity is expressed in units defined as the quantity of protein that specifically retains 10 ng of λ DNA on a nitrocellulose filter. Strains were dilysogenic derivatives of JM776.

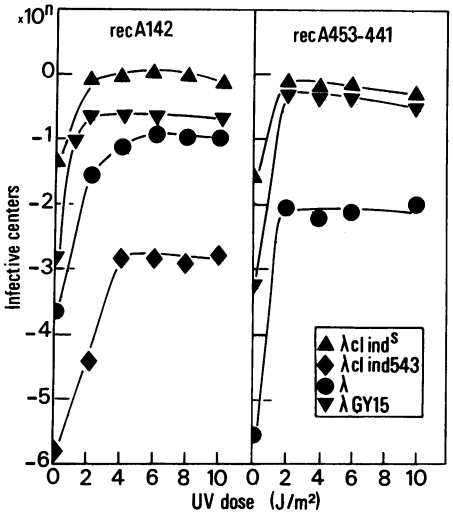

FIG. 5. UV induction of prophages in *recA142* and *recA453-441* lysogens. For *recA142*, GY5278 (●), GY5279 (▲), GY5250 (◆), and GY5270 (▼) were induced; for *recA453-441*, GY5265 (●), GY5267 (▲), and GY5273 (▼) were incubated at 32°C and induced. Induction was as described in the legend to Fig. 2.

protein is promoted by Tif activation or by UV irradiation. Tif activation (by adenine and elevated temperature) involves interaction with a normal replication fork (36). An Ind^r prophage was efficiently induced in a *recA441* host by Tif activation and not by UV irradiation. In contrast, an Ind^s prophage was induced in *recA453 recA441* mutants by UV irradiation and not by Tif activation. Tif activation seems particularly sensitive to the basal level of the RecA441 protein.

We have characterized the efficiency of prophage induction of a few λ mutants in various *recA* mutants. If in vitro, repressor cleavage seems to be a reaction of autodigestion, in vivo, prophage induction depends on four main factors: (i) the basal and induced cellular levels of RecA protein, (ii) the activability of RecA protein, (iii) the binding of RecA protein to phage repressors, and (iv) the induction sensitivity of phage repressors.

ACKNOWLEDGMENTS

The expert technical assistance of D. Bouillon and M. Pierre is gratefully appreciated. We are thankful to T. Horiuchi for providing the three λ*cI* mutants studied here. Discussions with A. Brandenburger, O. Reyes, and P. L. Moreau were profitable to this work.

M. Dutreix benefited from a fellowship from the Delegation Generale pour la Recherche Scientifique et Technique. Grants from the Ligue contre le Cancer, the Association pour la Recherche sur le Cancer, the Fondation pour la Recherche Medicale, and Euratom are gratefully acknowledged.

LITERATURE CITED

1. **Bailone, A., M. Blanco, and R. Devoret.** 1975. *E. coli* K12 *infA*: a mutant deficient in prophage λ induction and cell filamentation. Mol. Gen. Genet. **136**:291–307.
2. **Bailone, A., and R. Devoret.** 1978. Isolation of ultravirulent mutants of phage λ. Virology **84**:547–550.
3. **Bailone, A., and F. Galibert.** 1980. Nucleotide sequence of the operator of λ ultravirulent mutants. Nucleic Acids Res. **8**:2147–2164.
4. **Bailone, A., A. Levine, and R. Devoret.** 1979. Inactivation of prophage λ repressor in vivo. J. Mol. Biol. **131**:553–572.
5. **Castellazzi, M., J. George, and G. Buttin.** 1972. Prophage induction and cell division in *E. coli*. II. Linked (*recA, zab*) and unlinked (*lex*) suppressors of *tif-1* mediated induction and filamentation. Mol. Gen. Genet. **119**:153–174.
6. **Clark, A. J.** 1973. Recombination deficient mutants of *Escherichia coli* and other bacteria. Annu. Rev. Genet. **7**:67–86.
7. **Cohen, S., B. J. Knoll, J. W. Little, and D. W. Mount.** 1981. Preferential cleavage of phage lambda repressor monomers by recA protease. Nature (London) **294**:182–184.
8. **Devoret, R., and M. Blanco.** 1970. Mutants of *Escherichia coli* K12 (λ)$^+$ noninducible by thymine deprivation. I. Method of isolation and classes of mutants obtained. Mol. Gen. Genet. **107**:272–280.
9. **Devoret, R., M. Pierre, and P. L. Moreau.** 1983. Prophage φ80 is induced in *Escherichia coli* K12 *recA430*. Mol. Gen. Genet. **189**:199–206.
10. **Eshima, N., S. Fujii, and T. Horiuchi.** 1972. Isolation of λ*ind*$^-$ mutants. J. Genet. **47**:125–128.
11. **Flashman, S. M.** 1978. Mutational analysis of the operators of bacteriophage λ. Mol. Gen. Genet. **166**:61–73.
12. **George, J., M. Castellazzi, and G. Buttin.** 1975. Prophage induction and cell division in *E. coli*. III. Mutations *sfiA* and *sfiB* restore division in *tif* and *lon* strains and permit the expression of mutator properties of *tif*. Mol. Gen. Genet. **140**:309–332.
13. **Ginsburg, H., S. H. Edminston, J. Harper, and D. W. Mount.** 1982. Isolation and characterization of an operator-constitutive mutation in the *recA* gene of *E. coli* K12. Mol. Gen. Genet. **187**:4–11.
14. **Gottesman, M., and M. Yarmolinsky.** 1968. Integration negative mutants of bacteriophage lambda. J. Mol. Biol. **31**:487–505.
15. **Gussin, G. N., A. D. Johnson, C. O. Pabo, and R. T. Sauer.** 1983. Repressor and Cro protein: structure, function and role in lysogenization, p. 93–121. *In* R. W. Hendrix, J. W. Roberts, F. W. Stahl, and R. A. Weisberg (ed.), Lambda II. Cold Spring Habor Laboratory, Cold Spring Harbor, N.Y.
16. **Hopkins, N., and M. Ptashne.** 1971. Genetics of virulence, p. 571–574. *In* A. D. Hershey (ed.), The bacteriophage lambda. Cold Spring Habor Laboratory, Cold Spring Harbor, N.Y.
17. **Horiuchi, T., and H. Inokuchi.** 1967. Temperature-sensitive regulation system of prophage lambda induction. J. Mol. Biol. **23**:217–224.
18. **Levine, A., A. Bailone, and R. Devoret.** 1979. Cellular levels of the prophage λ and 434 repressors. J. Mol. Biol. **131**:655–661.
19. **Lieb, M.** 1981. A fine structure map of spontaneous and induced mutations in the λ repressor gene, including insertions of IS elements. Mol. Gen. Genet. **184**:364–371.
20. **Little, J. W.** 1984. Autodigestion of *lexA* and phage λ repressors. Proc. Natl. Acad. Sci. U.S.A. **81**:1375–1379.
21. **Little, J. W., and D. W. Mount.** 1982. The SOS regulatory system of *Escherichia coli*. Cell **29**:11–22.
22. **McEntee, K.** 1978. Studies of the *recA* and *lexA* genes of *Escherichia coli* K12, p. 349–360. *In* P. C. Hanawalt, E. C. Friedberg, and C. F. Fox (ed.), DNA repair mechanisms, vol. 9. Academic Press, Inc., New York.
23. **Moreau, P. L., A. Bailone, and R. Devoret.** 1976. Prophage λ induction in *Escherichia coli* K12 *envA uvrB*: a highly sensitive test for potential carcinogens. Proc. Natl. Acad. Sci. U.S.A. **73**:3700–3704.
24. **Moreau, P. L., M. Fanica, and R. Devoret.** 1980. Induction of prophage λ does not require full induction of RecA protein synthesis. Biochimie **62**:687–694.
25. **Mount, D. W.** 1971. Isolation and genetic analysis of a strain of *Escherichia coli* K12 with an amber *recA* mutation. J. Bacteriol. **107**:388–389.
26. **Mount, D. W.** 1977. A mutant of *E. coli* showing constitutive expression of the lysogenic and error-prone DNA repair pathways. Proc. Natl. Acad. Sci. U.S.A. **74**:300–304.
27. **Pabo, C. O., R. T. Sauer, J. M. Sturtevant, and M. Ptashne.** 1979. The λ repressor contains two domains. Proc. Natl. Acad. Sci. U.S.A. **76**:1608–1612.
28. **Phizicky, E. M., and J. W. Roberts.** 1980. Kinetics of RecA protein-directed inactivation of repressors of phage λ and phage P22. J. Mol. Biol. **139**:319–328.
29. **Quillardet, P., P. L. Moreau, H. Ginsburg, D. W. Mount, and R.**

Devoret. 1982. Cell survival, UV-reactivation and induction of prophage λ in *Escherichia coli* K12 overproducing RecA protein. Mol. Gen. Genet. **188:**37–43.

30. **Rebollo, J. E., P. L. Moreau, M. Blanco, and R. Devoret.** 1984. Restoration of RecA protein activity by genetic complementation. Mol. Gen. Genet. **195:**83–89.
31. **Roberts, J., and R. Devoret.** 1983. Lysogenic induction, p. 123–144. *In* R. W. Hendrix, J. W. Roberts, F. W. Stahl, and R. A. Weisberg (ed.), Lambda II. Cold Spring Harbor Laboratory, Cold Spring Harbor, N.Y.
32. **Roberts, J. W., and C. W. Roberts.** 1981. Two mutations that alter the regulatory activity of *E. coli* RecA protein. Nature (London) **290:**422–424.
33. **Roberts, J. W., C. W. Roberts, and D. W. Mount.** 1977. Inactivation and proteolytic cleavage of phage λ repressor *in vitro* is an ATP-dependent reaction. Proc. Natl. Acad. Sci. U.S.A. **74:**2283–2287.
34. **Sauer, R. T., C. O. Pabo, B. J. Meyer, M. Ptashne, and K. Backman.** 1979. Regulatory functions of the λ repressor reside in the amino terminal domain. Nature (London) **279:**396–400.
35. **Weinstock, G. M.** 1982. Enzymatic activities of the RecA protein of *Escherichia coli*. Biochimie **64:**611–616.
36. **Witkin, E. M.** 1982. From Gainesville to Toulouse: the evolution of a model. Biochimie **64:**549–555.