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Interaction of Bacteriophage K10 with Its Receptor, the *lamB* Protein of *Escherichia coli*

MICHÈLE ROA

Unité de Génétique Moléculaire, Département de Biologie Moléculaire, Institut Pasteur, Paris, France

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The *lamB* protein of *Escherichia coli* was initially recognized as the receptor for bacteriophage λ. It is now shown also to constitute the receptor for phage K10. The *lamB* protein interacts with phage K10 in vitro, but this interaction does not lead to phage inactivation. Most λ-resistant *lamB* mutants are also resistant to K10, and vice versa. However, a significant proportion of the mutants resistant to one of the phages is sensitive to the other. Nineteen K10-resistant λ-sensitive mutants have been studied. Only six of them produce a *lamB* protein which seems totally unimpaired in its interaction with λ. The mutations in these six strains all map in the same deletion interval of the *lamB* gene. The corresponding region of the *lamB* polypeptide must be specifically involved in the interaction with phage K10. An unusual pattern of K10 host range mutants has been obtained; two classes of such mutants could be defined, growing on two distinct classes of K10-resistant *lamB* mutants.

The outer-membrane proteins of gram-negative bacteria (7) generally play a role in at least two different classes of biological processes. On the one hand, they are involved in the transport of various molecules across the bacterial envelope (4). On the other hand, each of them constitutes part or all of the receptor for a specific set of phages or colicins (4; M. Schwartz, Recept. Recog. Ser. B, in press). The understanding of these processes in molecular terms will require precise knowledge of how the outer-membrane proteins interact with their various ligands. Attempts along this line are being performed for the *bfe* protein, which is involved in the transport of vitamin B-12 and which constitutes the receptor for phage BF23 and the E colicins (3), and for the *tonA* protein, which is involved in the transport of ferrichrome and constitutes the receptor for colicin M and phages T1, T5, and φ80 (10). The present work deals with the *lamB* protein, which plays a role in the transport of maltose and maltodextrins across the outer membrane and which constitutes the receptor for phage λ (19, 27, 28, 31). In addition to λ, two other phages have recently been reported also to use this protein as their receptor, i.e., K10 (9) and TP1 (30). In this paper the interaction of K10 with the *lamB* protein is compared with that of λ with the same protein.

MATERIALS AND METHODS

Bacterial and phage strains. The bacterial strains, all derived from *Escherichia coli* K-12, are listed in Table 1. Phages λV, λVho, and λVh_4h_{16}* (called λ, λh, and λhh*, respectively, for simplification) (12), T6 (23), and φ80 *psu* 3 (12) were from the laboratory collection. Phage K10 was a gift of P. Reeves (9), and phage BF 23 was from C. A. Schnaitman (21).

Chemicals, media, and standard techniques. The maltodextrins were prepared by limited hydrolysis of amylose (26, 31). Minimal medium M63, complete medium ML, and eosin methylene blue maltose agar were previously described (11, 20). Phages were grown by the agar overlay technique (16), using tryptone agar (1% tryptone [Difco], 0.25% NaCl, supplemented with 1.2% agar in the bottom layer and 0.6% agar for the top layer). Standard techniques of bacterial genetics were as described by Miller (16). Antisera against λ and K10 were obtained in rabbits and titrated by classic techniques (1, 5).

Isolation of K10-resistant mutants. Strains pop1306 and pop1311, both *trpE* (Am) and carrying the amber mutations *lamB506* and *lamB511*, respectively, were transduced to Trp^+ Dex^+, using φ80 *psu3* to yield pop 1327 and pop 1328. These suppressed strains were always grown in tryptophan-free maltose minimal medium to avoid loss of the suppressor. Drops (ca. 50 μl each) of saturated cultures of C600, pop 1327, or pop 1328 were deposited on minimum maltose agar plates overlaid with 1.4×10^{10} active particles of phage K10. After overnight incubation at 37°C, growth was generally confluent where the drops had been deposited. The mutants were reisolated from these spots by streaking on maltose minimum medium and tested for sensitivity to λ, λh, λhh*, K10, and φ80 *psu3* by cross-streaking against these phages on eosin methylene blue maltose agar. When the proportion of Mal^+ strains was to be estimated (K10-resistant derivatives of C600), the whole selection was performed in complete medium, and the mutants were streaked on eosin

TABLE 1. *Strains used*

Strain	Genotype	Origin/reference
C600	F⁻ *thr leu lacY1 supE tonA thi*	12
CR63	F⁻ *supD lamB63*	12
HfrG6	Hfr *his*	19
pop 715	F⁻ *thr leu tonA ΔmalB1*	18
pop 722	F⁻ *thr leu tonA ΔmalB9*	18
pop 723	F⁻ *thr leu tonA ΔmalB10*	18
pop 728	F⁻ *thr leu tonA ΔmalB15*	18
pop 735	F⁻ *thr leu tonA ΔmalB105*	18
pop 1021	Hfr *met A trpE9780*(Am) *gal rpoB*	27
pop 1076	pop 1078 *lamB5*	27
pop 1078	Hfr *trpE9780*(Am) *gal rpoB*	27
pop 1079	pop 1021 *lamB101*	27
pop 1081	pop 1021 *lamB103*	27
pop 1082	pop 1021 *lamB104*	27
pop 1083	pop 1021 *lamB105*	27
pop 1084	pop 1021 *lamB106*	27
pop 1085	pop 1021 *lamB107*	27
pop 1086	pop 1021 *lamB108*	27
pop 1087	pop 1021 *lamB109*	27
pop 1088	pop 1021 *lamB110*	27
pop 1090	pop 1021 *lamB112*	27
pop 1091	pop 1021 *lamB113*	27
pop 1111	pop 1078 *lamB63*	27
pop 1306	pop 1021 *lamB506*(Am)	18
pop 1311	pop 1021 *lamB511*(Am)	18
pop 1327	pop 1306 (φ80 *psu3*)	This work
pop 1328	pop 1311 (φ80 *psu3*)	This work
pop 1331 to pop 1336	pop 1327 *lamBN31* to *lamBN36*	This work
pop 1337 to pop 1357	pop 1328 *lamBN37* to *lamBN57*	This work
pop 1431 to pop 1457	pop 1331 to pop 1357 cured of the φ80*psu3* prophage	This work
pop 1730	Hfr *ΔmalB17*	27
pop 2047	F⁻ *gal rpsL ΔmalB107*	Braun-Breton
pop 3298	F⁻ *araD139 ΔlacU169 rpsL relA thi ΔmalB500*	17

methylene blue maltose agar.

Genetic analysis of the K10-resistant, λ-sensitive mutants. Genetic analysis of the K10-resistant, λ-sensitive mutants was performed on mutants derived from pop 1327 and pop 1328. These mutants carry a φ80 *psu3* prophage. Derivatives cured of this prophage were selected as λ-resistant Mal⁺ Trp⁻ lacking the immunity to φ80. The resulting strains carried two mutations in *lamB*, i.e., a promoter distal amber mutation which yields a λ-resistant, K10-resistant, Dex⁻ phenotype, and a presumptive missense mutation which, by itself, yields a K10-resistant, Dex⁺ phenotype. These strains were crossed with F⁻ strains carrying various deletions extending from *malK* into *lamB*. Dex⁺ recombinants occurred as a result of recombination events between the endpoint of the deletions and the *lamB* nonsense mutation. When all the Dex⁺ recombinants tested (about 100) were found K10 resistant, it was concluded that the deletion encompassed the site of the missense mutation leading to K10 resistance.

Preparation of bacterial extracts. To obtain crude membranes from HfrG6, the cells were disintegrated by passage through a French pressure cell (1,260 lb/in²), the extract was centrifuged at 200,000 × *g* for 45 min, and the resulting pellet was suspended in 10^{-2} M Tris-hydrochloride, pH 7.4. Cholate-EDTA extracts and pure *lamB* protein were prepared as previously described (19, 20). Peptidoglycan-*lamB* protein complexes were prepared as follows (J. Gabay, personal communication). The cells were grown to a density of 5 × 10^8/ml in 100 ml of M63 maltose, harvested, washed, and suspended in 5 ml of 2% sodium dodecyl sulfate–10% glycerol–2 mM $MgCl_2$–10 mM Tris-hydrochloride, pH 7.4. After a 30-min incubation at 60°C, the suspension was centrifuged at 100,000 × *g* for 1 h, and the pellet was suspended in 5 ml of 2% sodium dodecyl sulfate–10 mM Tris-hydrochloride, pH 7.4.

RESULTS

Description of phage K10. Phage K10 is morphologically similar to λ (Fig. 1), although it has a slightly more elongated head and perhaps a more flexible tail. Unlike λ, it is a virulent phage; it yields clear plaques, and the only bacteria which can be recovered from the center of the plaques are resistant mutants, rather than lysogens. In addition, K10 grows on λ lysogens. The structural proteins present in K10 phage particles are different in molecular weight from those present in λ particles (not shown). Antibodies directed against λ inactivate λ but not K10, whereas the reverse is true for antibodies directed against K10 (not shown). Maximal λ adsorption is obtained in 2 mM magnesium, whereas K10 adsorbs better in M63 minimal medium (containing 200 μg of bovine serum albumin per ml to protect the phage from spontaneous inactivation). Phages λ and K10 are therefore not closely related.

Evidence that K10 uses the *lamB* protein for its adsorption. Hancock and Reeves reported (9) that uncharacterized λ-resistant mutants were also resistant to K10. We verified that all mutants lacking the *lamB* protein, for instance *lamB* nonsense mutants (12, 18), are resistant to K10. If the *lamB* protein is the sole component of the K10 receptor, all K10-resistant mutants should be affected in the synthesis or the structure of this protein, as is the case for λ-resistant mutants (29). The synthesis of *lamB* protein can be affected by mutations occurring in the *lamB* gene itself, by mutations in *malT*, the positive regulator gene of the maltose regulon, or by polar mutations in *malK* (12, 18, 23, 29). The *lamB* mutants are Mal⁺ because the *lamB* protein is not required for growth on maltose at the concentration used in most culture media (0.2 to 0.5%), whereas *malT* and *malK* mutants are Mal⁻ (18, 23, 27). About 20% of the spontaneous or mutagen-induced, λ-resistant mutants are Mal⁺ (*lamB*), whereas 80% are Mal⁻ (mostly *malT*) (14, 23). Approximately the same

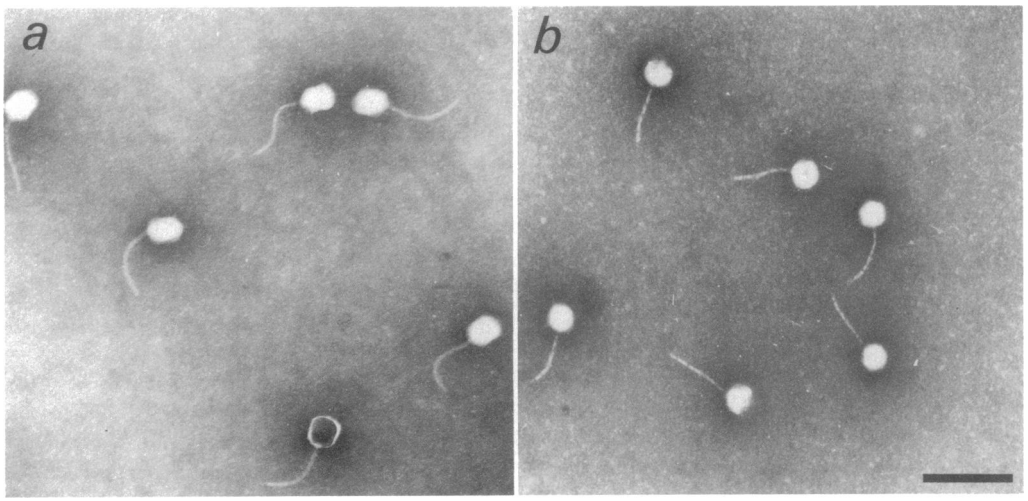

FIG. 1. *Electron micrographs of phage K10 (a) and lambda (b). Samples of purified preparations were deposited on grids, fixed with formaldehyde, and negatively stained with phosphotungstic acid as already described (20). They were examined under a Siemens Elmiskop 101 electron microscope. The bar represents 0.2 μm.*

relative proportions of Mal^+ and Mal^- strains were obtained after selecting for K10 resistance (data not shown). These results strongly support the conclusion that K10 and λ share the same receptor protein. This conclusion is further strengthened by the observation that antibodies directed against the *lamB* protein prevent the adsorption of both λ and K10 to sensitive cells but have no effect on the adsorption of phages T6 and BF23, which use different receptor proteins (Table 2) (15, 21).

Pattern of cross-resistance to λ and K10. The Mal^- strains which are obtained either as λ resistant or as K10 resistant are always resistant to both phages, and they will not be considered further.

Several λ-resistant Mal^+ strains were previously described (12). They were all *lamB* mutants, nonsense or missense. The nonsense mutants have been found resistant to all known host range mutants of λ (12) and unable to grow on maltodextrins containing more than three glucose residues (28, 31). These nonsense mutants, as stated above, are all K10 resistant. The missense mutants, on the other hand have all been found sensitive to at least one type of λ host range mutants (λhh*) and able to grow on maltodextrins (C. Braun-Breton, personal communication). Of 13 which were tested, 10 were resistant to K10 and 3 were sensitive (Table 3).

K10-resistant Mal^+ mutants were selected from a $lamB^+$ strain (C600) and, for reasons which will be explained in the next section, from strains carrying a late amber mutation in *lamB*, this mutation being suppressed by the amber suppressor *sup3*. Among the spontaneous mutants, none was λ sensitive (frequency less than 0.1%), whereas after ethyl methane sulfonate mutagenesis 4.6% of them had this phenotype (Table 4). Twenty independently isolated, K10-resistant, λ-sensitive mutants were chosen for further study. On 19 of these strains, λ plates with the same efficiency as on a wild-type strain. On one of them (pop 1338), however, λ has an efficiency of plating about 100 times lower. The 20 mutants grow on maltodextrins.

TABLE 2. *Inhibition of λ and K10 adsorption by antibodies directed against lamB*[a]

Final dilution of anti-*lamB*, antiserum	% of phage adsorbed on sensitive bacteria treated by antibodies against *lamB*			
	λ	K10	T6	BF23
10^{-1}	<1	<1	92	78
2×10^{-2}	38	68	90	90
2×10^{-3}	84	94	80	91
No antiserum	88	94	91	94
Preimmune, serum (10^{-1})	90	98	94	87

[a] Strain C600 grown to 5×10^8 cells/ml in minimal medium containing maltose was treated 1 h at 37°C with different dilutions of antiserum prepared against partially purified *lamB* protein (adsorption of nonspecific antibodies and inactivation of complement are as described in reference 8). Phage are then added at a multiplicity of infection of 1. After 15 min of adsorption, mixtures are centrifuged and appropriate dilutions of the supernatants are plated with indicator bacteria.

Mapping of mutations leading to K10 re-

TABLE 3. *Sensitivity of the lamB missense mutants to λ, K10, and their host range derivatives*[a]

lamB allele	Sensitivity to:					
	λ	λh	λhh*	K10	K10h$_A$	K10h$_B$
lamB$^+$	S	S	S	S	S	S
lamB103, 106, 110	R	S	S	S	S	S
lamB63, 101, 105, 107, 108	R	S	S	R	R	S
lamB104, 112	R	S	S	R	R	R
lamB5	R	R	S	R	R	S
lamB109, 113	R	R	S	R	R	R
lamBN31 to *lamBN57*[b]	S	S	S	R	S	R
lamBN34	S	S	S	R	S[c]	R
lamBN38	S[d]	S[d]	S[d]	R	R	R

[a] S, Sensitive; R, resistant.
[b] Except *lamBN34* and *lamBN38*
[c] No K10h$_A$ can be found on the strain carrying the *lamBN34* allele, but all the K10h$_A$ isolated on the other mutants plate with a reduced efficiency (about 10^{-4}) on this strain.
[d] Only partially sensitive (see text).

TABLE 4. *Phenotype of the K10-resistant mutants*

Mutant[a]	Total no. analyzed	% Sensitive		
		λhh*	λh and λhh*	λ, λh, and λhh*
Spontaneous	920	0.8	0.7	<0.1
EMS induced	1,200	7.7	5	4.6

[a] The spontaneous mutants were isolated from 6 independent clones, and the ethyl methane sulfonate (EMS)-induced mutants were from 36 independent clones.

sistance. Stocks of phage P1 were grown on two K10-resistant, λ-sensitive mutants isolated from the *lamB*$^+$ strain C600. These stocks were then used to transduce a strain (pop 2047) deleted for the *malK-lamB* operon. All the Mal$^+$ transductants (40 of 40 in each case) were K10 resistant and λ sensitive. The latter phenotype, therefore, most likely results from a mutation in *lamB*. To map more precisely this type of mutation within *lamB*, it was necessary to devise a special technique because there exists no obvious selection for K10-sensitive recombinants issued from crosses between K10-resistant parents (see Materials and Methods).

Twenty mutations leading to a K10-resistant, λ-sensitive phenotype were mapped by this technique. The results indicate a definite clustering of these mutations (Fig. 2). Seven of them map in interval VI, and 13 map in interval VIII or IX. This distribution is very different from that of the amber mutations in the same gene (18). Since it seemed possible that the mutations in the two clusters might lead to slightly different phenotypes, the corresponding mutants were further characterized.

Two phenotypic subclasses of K10-resistant, λ-sensitive mutants. Strains carrying six of the K10 resistance mutations clustered in interval VI adsorb λ at the same rate as wild type, whereas those carrying mutations in interval VIII or IX adsorb at a greatly reduced rate (data not shown). Normal λ receptor activity (19) is present in the extracts of the six mutants constituting the first class, whereas it is about 100-fold lower in the extracts of the second class (Table 5). The amount of *lamB* protein present in the latter mutants is essentially normal, as visualized by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (2) of whole-cell ex-

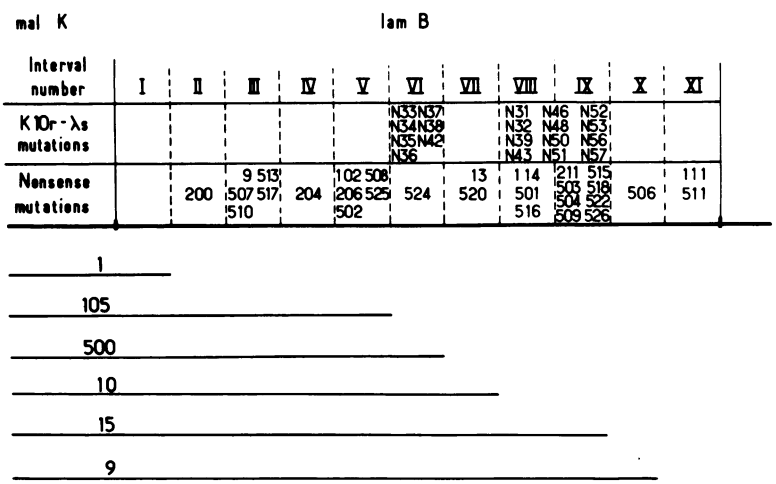

FIG. 2. *Genetic localization of K10-resistant, λ-sensitive mutations. The deletion intervals were defined previously (18). Only the deletions used in this work are shown here, represented by lines below the map. The mapping technique did not make it possible to distinguish between intervals VIII and IX (see reference 18).*

TABLE 5. λ *Receptor activity in cholate-EDTA extracts of the K10-resistant, λ-sensitive strains*[a]

lamB allele	% Activity
lamBN31	2
lamBN32	2
lamBN33	100
lamBN34	32
lamBN35	80
lamBN36	100
lamBN37	56
lamBN38	8
lamBN39	<1
lamBN42	100
lamBN43	<1
lamBN46	<1
lamBN48	<1
lamBN50	<1
lamBN51	<1
lamBN52	<1
lamBN53	<1
lamBN56	<1
lamBN57	<1

[a] Receptor activity was determined from the rate of inactivation of λh by using proper dilutions of the cholate-EDTA extracts (18). The results are expressed as percent activity in the parental strains pop 1327 and pop 1328. *K*, the first-order rate constant for λh inactivation in undiluted extracts, was found very close to 5 s^{-1} with the extract from both of the parental strains.

tracts or of peptidoglycan-*lamB* protein complex (not shown). The low λ receptor activity in extracts of these strains can therefore be attributed to a structural modification of the *lamB* protein, rather than to a decrease in its quantity. Nineteen K10-resistant mutants on which λ grows normally therefore fall into two classes defined by both their phenotype and the genetic location of their mutation. Strain pop 1338 represents an additional class by itself, since λ plates with a strongly reduced efficiency on it. Its mutation maps in interval VI.

Host range mutants of phage K10. We found no host range mutant of K10 which would grow on *lamB* nonsense mutants (frequency less than 10^{-10}), but two classes arose when K10 was plated on two classes of *lamB* missense mutants (Table 3). The first, $K10h_A$, can be obtained by plating K10 on the K10-resistant strains which are fully sensitive to λ. Host range mutants selected on one of these strains always grow on the other K10-resistant strains of the same class, and on the wild-type strain. The second class, $K10h_B$, grow on certain of the K10-resistant, λ-resistant strains listed in Table 3 and on wild-type.

The $K10h_A$ phages do not grow on the bacterial mutants which allow growth of $K10h_B$ phages and vice versa. These two types of host range mutants are obtained at a low frequency (about 10^{-9}). For other phages, artifactually low frequencies have been obtained for host range mutants because phage particles bearing the host range character were unstable or sensitive to chloroform (12, 19, 30). In the present case, however, the frequency of host range mutants was low even in fresh phage stocks not treated with chloroform.

Interaction between K10 and the *lamB* protein in vitro. The plaque-forming ability of phage K10 was found unaffected by the addition of envelope fragments, cholate-EDTA extracts, or purified *lamB* protein, all from HfrG6 cells. In this respect, K10 behaves like λ (20, 24). However, the addition of chloroform or ethanol to the phage-receptor mixtures, the use of *lamB* protein from *Shigella sonnei*, or the use of host range mutants of the phage, all conditions which lead to the inactivation of λ (12, 19, 20, 25), are without effect on the viability of phage K10. The existence of an interaction between K10 and the *lamB* protein in vitro could only be demonstrated by a competition experiment. The inactivation of λh by membranes containing *lamB* protein was indeed significantly slowed down when an excess of K10 phage was added (Fig. 3). From the concentration of phage K10 which must be added to reduce by a factor of 2 the rate of λh inactivation, the constant K_a characterizing the equilibrium between K10 and the *lamB* protein can be estimated to be in the range of 10^{10} M^{-1}.

DISCUSSION

The evidence that phage K10, like phage λ, uses the *lamB* protein as its receptor can be summarized as follows: (i) all K10-resistant mutants isolated so far synthesize a *lamB* protein which is either modified or produced in strongly reduced amounts; (ii) the adsorption of phage K10 to sensitive cells is inhibited by antibodies directed against the *lamB* protein; and (iii) phage K10 interacts with the *lamB* protein in vitro. Even though they share the same receptor protein, phages λ and K10 do not seem to have identical adsorption organelles, since antibodies directed against one phage fail to inactivate the other, and vice versa.

A comparison of the interactions of the two phages with the *lamB* protein revealed a few differences. The optimum ionic conditions for the interaction in vivo and in vitro are not the same for the two phages. In 2 mM $MgSO_4$, the affinity of K10 for the *lamB* protein ($K_a = 10^{10}$ M^{-1}) is about 200 times lower than that of λ (24). In addition, several conditions are known under which λ is irreversibly neutralized by the

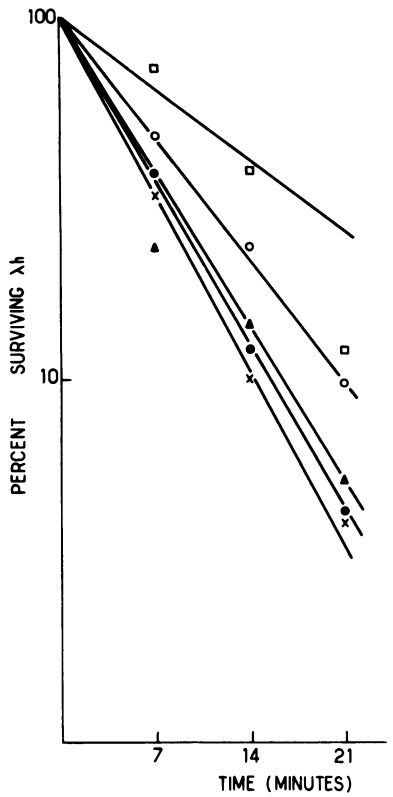

FIG. 3. *Competition between K10 and λh for the lamB protein in vitro. HfrG6 membranes containing about 3.6 × 10^{13} active molecules of lamB protein per ml, as estimated by λh inactivation (19), were diluted 10^3 times in 10 mM Tris-hydrochloride (pH 7.5). Portions were mixed with an equal volume (100 μl) of 4 mM $MgSO_4$ containing 1.8 × 10^{10} (●), 3.6 × 10^{10} (▲), 1.8 × 10^{11} (○), 3.6 × 10^{11} (□), or no (×) plaque-forming units of phage K10. After 5 min at 37°C (i.e., t_0), 200 μl of 4 mM $MgSO_4$ containing 2.5 × 10^8 plaque-forming units of λh was added in each tube, and portions were taken at 0, 7, 14, and 21 min. Appropriate dilutions were plated with λh-sensitive, K10-resistant indicator bacteria (CR63). Essentially the same results were obtained if purified λ receptor was used instead of crude membranes.*

lamB protein in vitro, whereas no such conditions were found in the case of K10. An indication that different, albeit overlapping, sites of the *lamB* protein interact with λ and K10 comes from an analysis of the phage-resistant mutants. From a previous study it appeared that most of the λ-resistant *lamB* mutants which were missense were sensitive to λhh*. Of 13 such mutants analyzed in the present work, 3 were sensitive to K10. Conversely about 5% of the K10-resistant mutants were found sensitive to λ. However, if one excludes the mutants which are resistant to λhh* as being probably devoid of *lamB* protein (nonsense or other), the proportion of λ-sensitive mutants among the presumed missense K10-resistant mutants becomes about 26%. In other words, if one only takes into account the missense mutants, about one-fourth of the λ-resistant mutants are sensitive to K10 and vice versa. The mutants resistant to only one of the two phages are presumably affected in a portion of the *lamB* polypeptide which specifically interacts with this phage. In an attempt to define one or several parts of the polypeptide interacting with phage K10, 19 different K10-resistant, λ-sensitive mutants were analyzed in some detail. Only six of them adsorbed λ like a *lamB*$^+$ strain and produced a *lamB* protein interacting normally with λ in vitro. The mutations in these six independently isolated mutants were found to be all clustered in a single deletion interval of the *lamB* gene. Conceivably, these six mutations may have affected the same amino acid specifically involved in the interaction of the *lamB* protein with phage K10. Such a possibility would not be incompatible with the rather low frequency of these mutations. The results do not yet allow us to conclude whether the peptide or amino acid affected in these six mutants is the only one to be specifically involved in the interaction with phage K10. Before such a conclusion can be drawn, a much larger number of mutants ought to be analyzed, selected from populations treated with various mutagens (6).

The present work suggests that K10 and λ do not interact in exactly the same manner with the *lamB* protein. It will be interesting to find out whether these differences in phage-receptor interaction are accompanied by differences in the process of DNA injection. It is noteworthy, in this respect, that phage K10 grows normally on bacterial mutants, called *pel* (22), on which phage λ fails to inject its DNA (unpublished data).

The pattern of host range mutants isolated from K10 is rather unusual. Two classes of such mutants have been obtained: those growing on most of the K10-resistant, λ-sensitive *lamB* mutants ($K10h_A$), and those growing on some of the K10-resistant, λ-resistant *lamB* mutants ($K10h_B$). No phage mutant has been obtained which would grow on both classes of bacterial mutants. For most of the other phages which have been studied, the host range mutants could be classified in an order of increasing "potency" according to the number of phage-resistant mutants on which they could grow (Schwartz, Recept. Recog. Ser. B, in press). These host range mutants could be interpreted as "trigger-happy" phages, able to undergo an irreversible adsorption even when their interaction with the recep-

tor is imperfect. The two classes of K10 host range mutants cannot be classified in order of increasing potency. They may correspond to different modifications of the adsorption organelle(s), leading to the recognition of different classes of mutant receptors. A similar conclusion was reached for the host range mutants of the flagellotropic phage χ1 (13).

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