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<td>Author(s)</td>
<td>清水，喜久雄</td>
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<td>Citation</td>
<td>大阪大学，1990，博士論文</td>
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<td><a href="https://doi.org/10.11501/2964165">https://doi.org/10.11501/2964165</a></td>
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FUNCTION OF SINGLE-STRANDED DNA-BINDING PROTEIN OF BACTERIOPHAGE T7

KIKUO SHIMIZU

1990
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Preface

Bacteriophage T7 is one of the phage studied extensively, and the mechanism of its DNA replication and recombination is well known.

Genetic cross-experiments of bacteriophage T7 suggested that products of the genes 2.5, 3, 4, 5, and 6 are required for recombination as well as DNA replication (1-3). To elucidate roles of these products in recombination, isolation of the intermediate molecules of genetic recombination was carried out from the T7-infected cells under the absence of each of these functions (4, 5). Based on these results, roles of the relevant gene products were hypothesized as follows. Gene 6 product, 5'-exonuclease, makes gaps from nicks, which have been introduced at random or specifically. Gapped molecules can pair each other with their complimentary gapped regions and form a doubly branched molecule with letter H structure. In these processes, single-stranded DNA-binding protein (ssb, the product of the gene 2.5) is involved and stimulates formation of the doubly branched molecules. Gene 3 product, endonuclease, processes the branches to form a linear recombinant molecule. T7 DNA polymerase, specified by the gene 5, stimulates formation of the branched molecules by its exonucleolytic activity and/or repair activity by a single strand-replacing synthesis.

T7 ssb plays also an important role in DNA replication in vitro. It stimulates the polymerization activity of T7 DNA polymerase on single stranded templates, and also stimulates the exonuclease activity of T7 DNA polymerase on a duplex DNA template (6,7). T7 5'-exonuclease activity of the gene 6 product was also stimulated by T7 ssb (8). In vitro, E.coli ssb protein could substitute for T7 ssb with regard to its stimulatory effect on the activity of T7 DNA polymerase (9). This result suggested that T7 ssb was not essential for T7 phage growth, but could be replaced by E.coli ssb.

Both replication and recombination of DNA are important for the transfer of genetic information, and T7 ssb participates in both process, and it is believed to interact with several proteins which participate in replication and recombination.
In this work, I will describe the isolation and characterization of a temperature sensitive ssb mutant and amber mutants, and will show that T7 ssb is essential for the phage growth. I will also present the evidence that T7 ssb interacts with other T7 coded proteins, exonuclease (gene 6 product) and gene 18 product.

The regulation of expression regulation of the gene 2.5 operon was also suggested.

Kikuo Shimizu
Citations for preface


(7) Roberts, L., Sadowski, P. & Wong, J. 1982 Specific stimulation of the T7 gene 6 exonuclease by the phage T7 coded deoxyribonucleic acid binding protein Biochemistry 21: 6000-6005


CHAPTER I

Isolation and characterization of the gene 2.5 mutants
CHAPTER I

Abstract

We isolated three new mutants in the gene 2.5 which encodes a single-stranded DNA binding protein, ssb (232 amino acids) of bacteriophage T7. One is a temperature sensitive mutant ts2.5, which was isolated after mutagenization with NTG in the phage infected cells. The others are amber mutants (am2.5-1 and am2.5-2) whose mutations were introduced by in vitro mutagenesis.

The am2.5-1 mutation was designed to encode a 15 amino acids polypeptide and am2.5-2 to encode a 200 amino acids polypeptide.

All these mutants could not make viable progeny under the restrictive condition, at 42°C or in suppressor free host bacteria even if the bacterial had the wild type ssb gene.

These results, however, rendered us a suspicion against T7 up2 mutant, whose growth was dependent the host ssb (Araki and Ogawa, 1981).

The analysis of T7 up2 revealed that the mutation in the gene 2.5 of T7 up2 was an opal mutation, op1, and this mutant gene encoded a protein lacking 17 amino acid residues from C-terminal.

Moreover we found that T7 up2 mutant had two other mutations outside the ssb gene, that enabled T7 phage to use bacterial ssb.

The locations of these mutations on T7 phage genome were roughly determined by replacing each part of the mutant DNA by the corresponding wild type DNAs in vitro. Their precise locations were then determined by the genetic cross experiments. One mutation was found in the gene 6 and the other was in the gene 18. Those two mutations had no phenotype by themselves. Moreover, the phage that has op1 mutation alone (T7 op1) could not grow on su− strain even if the host strain had the ssb+ gene.

The recombination and DNA synthesizing abilities of T7 ssb mutants were measured. The both abilities of T7 op1, am2.5-1 and am2.5-2 phages were reduced on nonpermissive host as expected from the results of T7 up2 phage, but T7 ts2.5 synthesized DNA at nonpermissive temperature unexpectedly. The synthesized DNA in
T7 ts2.5 infected cells at nonpermissive temperature were revealed to be concatemeric DNA by the density gradient sedimentation analysis.
CHAPTER I

Introduction

A single-stranded DNA-binding protein (ssb) exists universally in living organisms (Stephen C et al. 1981). These proteins are generally a single-chain protein with a molecular weight close to 30,000. In spite of a small size protein, ssb takes is involved in DNA replication and recombination in E.coli and bacteriophage (Morrical, Lee and Cox 1986). The ssb of bacteriophage T7 plays an important role for its DNA replication and recombination. In replication, ssb stabilizes the single stranded region of DNA during lagging strand replication (Delius, Mantell and Alberts 1972). In recombination, ssb enhances the activity of 5'-exonuclease (gene 6 product) (Sadowski 1984).

The mutant of ssb of bacteriophage T7 had not been available recently although the ssb protein of bacteriophage T7 was purified. It was thought that one of the reason why the mutant had not been available was substitution of ssb defect in T7 phage with the bacterial ssb. Actually, this kind of substitution was observed for the mutations in the gene 1.3 (ligase) and the gene 1.2 (replication factor). T7 ligase mutant was not isolated until ligase deficient bacterial strain was used for (Masamune, Frankel and Richardson 1971), and E.coli optA product was found to be able to substitute for the phage gene 1.2 protein (Saito, Tarbor, Tamanoi and Richardson 1980; Saito and Richardson 1981).

Based on the above consideration, the mutant of ssb of T7 phage, up2 was isolated by using E. coli ssb deficient strain at our laboratory, and named as the gene 2.5, since it was between the gene 2 and the gene 3 (Araki and Ogawa 1981a), and Studier isolated T7 ssb mutant, J27a by the gel electrophoresis for altered T7 ssb protein (1981).

In this paper, we will describe the characteristics of T7 up2 and findings that T7 up2 strain bears three mutations: an opal mutation in the gene 2.5 and two other mutations in the gene 6 and the gene 18. These two mutations outside the gene 2.5 allow the mutant to grow on E. coli sup+ ssb+ strain when the product of gene 2.5 was deficient. Moreover we isolated the new mutants of ssb which have no activity at non-permissive
condition and characterized them to consider the roles of ssb gene \textit{in vivo}. The results show that T7 ssb protein is necessary to DNA replication, recombination and repair, and that \textit{E.coli} ssb cannot substitute for phage ssb \textit{in vivo}. 
Materials and Methods

Buffers and Media:

T-broth contains 1% Bactotryptone (Difco) and 0.25% (w/v) NaCl.

Cas-λ broth contains 1% Casamino Acids (Difco, vitamin-free), 0.55 NaCl and 1μg/ml vitamin B1 (pH 7.0). M9 medium was described previously (Tsujimoto and Ogawa 1977). T7 buffer contains 10 mM Tris-HCl (pH 7.4), 1 mM MgSO4, 5% NaCl and 10 mg/ml gelatin. TEN buffer contains 10 mM Tris-HCl (pH 7.4), 1 mM EDTA and 10 mM NaCl.

SSC contains 0.15 M NaCl and 0.015 M sodium citrate (pH 7.0). All of radioisotopes were purchased from Amersham, Japan.

Enzymes and Chemicals:

Restriction enzyme EcoRI was prepared as described by Wilson and Young (1975). Restriction enzyme BglII, BciI, BstEIi, and XbaI were purchased from Takara-Shuzo, Japan, and New England Biolab, U.S.A. T4 DNA ligase was purified as described by Weiss et al. (1968). T4 polynucleotide kinase was purified as described by Richardson C. C. (1965). Low melting temperature agarose was purchased from BioRad Lab, U.S.A. BU was purchased from YAMASA. Oligonucleotide-directed mutagenesis system (ver.2) was from Amersham. T7 sequencing kit was from Pharmacia.

DNA and Oligonucleotides:

M13mp18 DNA was purchased from Takara. The 36 mer (5'--GGGTACCGCTGA-ACCTAGGCTTACATCGCCAAGC-3') for introducing am2.5-1 mutation was synthesized by DNA synthesizer (Applied Biosystems) in our laboratory, and two 17 bp oligonucleotides, (5'--GAGGTTACTCGTGTGC-3') for DNA sequencing, (5'--ATGTTGCTAGGTTCTGCC-3') for introducing am2.5-2 mutation were purchased from Takara.
Bacterial and Phage strains:

Bacterial strains and T7 phage strains used in this CHAPTER were described in Table 1. and Table 2. respectively. T7 opI mutation in the gene 2.5 was separated from up2 (Araki and Ogawa 1981a). T7 amber mutants were obtained from Dr. F. Studier (1969).

Isolation of mutants:

T7 wild type phage was mutagenized by following procedure.

_E.coli_ B, 011' was grown to 3 x 10^8 cells/ml in T-broth supplemented with 1 mM MgSO_4_. To the culture NTG*1 was added to a final concentration of 200 μg/ml and the bacterial cells were infected with T7 wild type phage at a multiplicity of 0.1. The mixture was incubated until complete lysis occurred. After complete lysis occurred, the lysate was centrifuged at 8,000 rpm for 10 min at 4°C to remove debris and the supernatant was recentrifuged to remove residual NTG at 36,000 rpm for 1 hr at 4°C in Beckman sw 50.1 rotor. The pellet was suspended in T7 buffer.

Mutagenized phages were plated with an overnight culture of 011' at 32°C.

Cloning of T7 gene 2.5 region:

The _BclI-BglII_ region (3120bp) of T7 DNAs were cloned into the _BamHI_ site of M13mp18 DNA for DNA sequencing and oligonucleotide-directed mutagenesis.

The _BclI-BglII_ region includes the genes 2-3.5.

Sequencing of mutant DNA:

Sequencing of mutant DNA was carried out based on M13 method using Pharmacia T7 sequencing kit. Method of cloning of the fragment containing the gene 2.5 mutations was described in the text.

Oligonucleotide-directed mutagenesis:
CHAPTER I

Mutagenesis was carried out by Amersham oligonucleotide- directed mutagenesis system (ver 2).

Transfer of Mutations into T7 phage:

The gene 2.5 mutations introduced by the site directed mutagenesis were transferred from M13 phage DNA into T7 phage DNA by in vitro recombination. T7 DNA was digested by restriction enzymes Tth1111 which cuts at the 8,894th base and BglII which cuts at the 11,515th base. M13 phage DNA was digested by restriction enzymes Tth1111 and Sau3A. The digested M13 DNA was applied to agarose gel electrophoresis and 2,622bp fragment was isolated from the agarose. Digested T7 DNA and 2,622bp M13 DNA fragment were mixed and ligated by Takara ligation kit. E.coli C600r-m-recB was transfected with the ligated DNA by the standard method.

The plaques appeared were picked up and analyzed the plating efficiency on various hosts. T7 DNA was isolated and screened for appropriate restriction sites.

UV irradiation:

Phage stocks were diluted to $10^9$ phages/ml in T7 buffer and irradiated in a glass petri dish with constant agitation under a 15-watt low-pressure germicidal lamp at a dose rate about 1.0 J m$^{-2}$ sec$^{-1}$. Irradiated samples were plated and incubated under the dark to avoid photoreactivation.

Analysis of mutant proteins of ssb:

Bacterial strain 594 was grown to the density of $3 \times 10^8$ cells/ml in M9 medium supplemented with 0.2% Glucose and 0.2% Casamino Acid (Difco). The culture (5 ml) was irradiated by UV light at a dose of 1000 J/m$^2$. After culturing further for 30 min, the cells were infected with T7 phage at a multiplicity of 20. After 5 min of infection, $^{35}$S-Methionine (43.8 GBq/μmol) was added to the cultures at an specific activity, 37 KBq/ml. After 15 min of incubation, the infected cells were collected by centrifugation at 8000 rpm at 4°C for 10 min. The pellet was suspended in 0.1 ml of
SDS buffer, and was heated at 95°C for 5 min. The sample was subjected to SDS gel electrophoresis by Laemmli's method (Laemmli 1970).

Measurement of DNA synthesis:

Bacterial cells were grown to the density of $3 \times 10^8$ cells/ml in M9 medium supplemented with 0.2% Glucose, 0.2% Casamino Acids, 2 µg/ml thymine, and irradiated with UV at a dose of 500 J/m². After incubation at 37°C for 30 min further $[^3H]$-thymidine (1.67 GBq/µmol) was added to the culture at 37 KBq/ml. After 5 min, phages were added to each culture at a multiplicity of 10. At a time indicated, 100 µl of samples were removed and added with the equal volume of 10% TCA *2 and chilled on ice, and their acid-insoluble radioactivities were determined.

Preparation of labeled phages:

$[^32P]$-labeled or $[^3H]$-labeled T7 phage was prepared as described previously (Shimizu, Araki and Ogawa, 1985) except that bacterial host 011' was used instead of C600thyA. $[^3H]$-BU-labeled phage was prepared by the following procedure. 011' cells were grown to $1 \times 10^8$ cells/ml in Cas-λ broth supplemented with 4 µg thymine/ml at 37°C, and harvested by centrifugation at room temperature and resuspended in Cas-λ broth supplemented with 10 lg BU*3, 1 µg thymine, and 37 KBq $[^3H]$-thymidine (1.67 GBq/µmol) per ml. After culturing for 90 min, cells were infected with T7 phage at a multiplicity of 0.1. After complete lysis occurred, phages were purified by differential centrifugations and banding in a CsCl density gradient.

Isolation of intermediate molecules in recombination:

Bacterial strain 594 was grown to the density of $3 \times 10^8$ cells/ml in T-broth supplemented with 1 mM MgSO₄ at 32°C or 42°C. $[^32P]$-labeled and $[^3H]$-BU labeled phage was added to the culture at a multiplicity of 10 each. After adsorption for 5 min, the infected cells were shaken for 10 min and collected by centrifugation by 8,000 rpm at 4°C. The pellets were suspended in SSC with 100 mg/ml lysozyme. The solutions
were treated with 3 cycles of freezing and thawing in dry ice/acetone bath, and added with Pronase and SLS at a concentration of 1 mg/ml and 1%, respectively. The mixtures were incubated at 37°C for 1 hr, and then followed with CsCl density gradient centrifugation.

**Analysis of intracellular DNA in T7 phage-infected cells:**

*E. coli* 594 was grown at 30°C to $3 \times 10^8$ cells/ml in M9 medium. The culture was divided into 4 parts. Each portion was infected with one of the following phage; T7 wild type, T7 *opI*, T7 *opIS-1*, and T7 *opIS-2* at a multiplicity of infection of 10. At 8 min after infection $[^{3}\text{H}]$-thymidine(1.67 GBq/μmol) was added to each infected culture at 37 KBq/ml. At 10 min after infection samples were ice chilled with TEN-buffer. The DNA was extracted by the method described previously (Shimizu, Araki and Ogawa 1985) and analyzed by neutral sucrose gradient sedimentation with $[^{32}\text{P}]$-labeled marker T7 DNA (Miller and Marion 1976). After centrifugation the sample was collected from the bottom of a tube and acid-insoluble radioactivity was determined. Almost all $[^{3}\text{H}]$-labeled DNA was found in the newly synthesized T7 DNA which was identified by DNA-DNA hybridization (Miller and Marion 1976). The $[^{32}\text{P}]$-labeled marker DNA was extracted from $[^{32}\text{P}]$-labeled T7 phage particles.

**Extraction of Phage DNA:**

Purification of phage and preparation of phage DNA was described previously (Shimizu, Araki and Ogawa 1985).

**Genetic cross of T7 phages:**

One of fresh culture of *E. coli* grown in T-broth supplemented with 1 mM MgSO$_4$ to $2 \times 10^8$ cells/ml was added with freshly prepared parental T7 phages at a multiplicity of infection of 10 each.
CHAPTER I

The infected cells was kept standing at 37°C for 5 min, and then treated with T7 phage specific antisemur at a final K value of 5 for 5 min at 37°C. The infected cells were diluted 1:10^3 with T-broth and the number of infective centers/ml was measured.

The diluted infected cells were was incubated at 37°C for 1 hr. to allow phage growth. The recombination frequency was deduced by calculating from the ratio of number of progeny phages on non-permissive host to those on permissive host.

Transfection of bacterial cells by T7 phage DNA:

Transfection of bacterial cells by T7 DNA was carried out by the method of Cameron et al. (1975).

Construction of recombinant T7 DNA:

T7 up2 DNA was digested with appropriate restriction enzyme and subjected to agarose gel electrophoresis (low melting agarose 0.4%) at constant voltage of 6 V/cm. A slice of agarose gel containing the band of interest was cut out. Then DNAs were eluted from the slice by following procedure: the slice was melted at 65°C and added with an equal volume of water saturated phenol. After shaking, the mixture was centrifuged at 8,000 rpm at 4°C for 20 min. The same phenol extraction was repeated again. Then DNA was precipitated with 70% EtOH. The recovery of DNA from agarose was about 70%. Ligation of DNA was carried out with T4 DNA ligase at 12°C. ZEN2 (carrying both amber and opal suppressors) strain was transfected with the ligated DNAs.

The plaques were picked up by Pasteur pipettes and were put into a log-phase culture of Q1sup71. After complete lysis occurred, the phages were plated on appropriate bacterial host.

Determination of nucleotide sequence:

After cleaving T7 up2 DNA by KpnI and AvaI restriction endonucleases, the KpnI-AvaI fragment (nucleotide 9,193-10,512) was separated by polyacrylamide gel electrophoresis and isolated from the gel and the 5' ends of fragments were labeled with
by using T4 polynucleotide kinase. The AluI fragment (nucleotide 9,802-10,199) or HindIII fragment (nucleotide 9,675-9,821) was isolated by the same procedure as KpnI-AvaI fragment and the 5' ends of their fragments were labeled with [32P] similarly. After cleaved by HhaI (for the AluI fragment) or TaqI (for the HindIII fragment, the AluI-HhaI fragment (nucleotide 9,802-9,926) and HindIII-TaqI fragment (9,691-9,821) were isolated by polyacrylamide gel electrophoresis and sequenced by the method of Maxam and Gilbert (1979). The sequenced nucleotides were in r strand from HindIII site at nucleotide 9,824 to 9,769 and in l strand from AluI site, 9,802 to 9,861. The number of nucleotide and the nomenclature of T7 DNA strands are defined according to Dunn and Studier (1981).

Measurement of burst size:

The burst sizes of opI and newly isolated phages on several hosts were measured by the method described in Studier (1969).
CHAPTER 1

Results

Isolation of a temperature sensitive mutant in the gene 2.5:

The mutant of the gene 2.5 of T7 phage was primarily isolated by Araki and Ogawa (1981a). This mutant, _up2_, made a truncated ssb protein which lacked 17 amino acids residues from C-terminal. (Araki, Shimizu and Ogawa 1990). This mutant protein could bind to double stranded DNA effectively as well as single-stranded DNA unlike the wild type ssb protein. In order to clear the roles of ssb protein in DNA replication, recombination or phage growth, I attempted to isolate a ssb mutant which lost the function completely by introducing an amber mutation or temperature sensitive mutation.

One temperature sensitive mutant (_ts2.5_) which could not complement _am1-am19_ mutations at 42°C was isolated after screening 3000 mutagenized phages. The mutated gene was mapped by genetic cross (data not shown). The mutation site was between the gene 2 and the gene 3, and was determined by nucleotide sequencing. The mutant T7 phage DNA was digested with _BclI_ and _BglIII_, and 3.2 kb fragment which included T7 gene 2.5. was isolated after gel electrophoresis. The isolated fragment was inserted into a _BamHI_ site on M13mp18 vector DNA (Figure 1.).

The nucleotide sequence of the cloned fragment on the M13mp18bb was determined by M13 methods. In this cloning, I always got the gene 2.5 on the vector in an opposite polarity but not in order polarity at the down stream of _lacZ_ promoter. This region also could not be cloned into pMB9 (Campbell _et al._ 1978), pBR322 or pUC118 (our results). Moreover M13mp18bb is very unstable and about 80% of M13mp18bb had a deletion during overnight propagation. _T7 ts2.5_ was found to have two mutations. One was the change of G to A of nucleotide 9,587, which caused the change, glycine to serine, and the other was the change of G to A of nucleotide 9,804, which changed trp codon (TGG) to the stop codon (ATG). The later mutation happened to affect the same amino acid as _opl_ mutation occurred. The efficiency of plating (E.O.P.) of the mutant strains at 32°C or 42°C was shown in Table 3. E.O.P. of this mutant on ssb* bacteria
which has no amber suppression at 42°C was $10^{-5}$, and E.O.P. on ssb$^+$ su$^{+2}$ was $10^{-3}$. The result means that ts2.5 mutant could not grow at 42°C if even host strain has the wild type ssb gene. Isolation of amber mutants in the gene 2.5 by *in vitro* mutagenesis: Two amber mutants in the gene 2.5 were isolated by *in vitro* mutagenesis. The outline of the isolation procedure is shown in Figure 2. The mutation sites of *am2.5-1* which is at the 15th amino acid from N terminal and *am2.5-2* which is at the 202nd amino acids from N terminal were confirmed by digestion with restriction enzymes, Eco8I1 (for *am2.5-1*) and EcoT14I (for *am2.5-2*). Both mutation sites had been designed to create a sensitive site for Eco8I1 or EcoT14I. The mutation sites and the nucleotide sequence and amino acids sequence are shown in Figure 3, and the plating efficiency of each phage is shown in Table 3. The efficiencies of *ts2.5*, *am2.5-1* and *am2.5-2* on non permissive condition were about $10^{-5}$, except *ts2.5* on 594su$^{+2}$ at 42°C. It was $10^{-3}$ and meant that the *ts2.5* was partially suppressed by su$^{+2}$ amber suppressor.

A nonsense mutation, *op1* in the *up2* mutant:

A T7 nonsense mutant which cannot grow on the su$^+$ssb defective strain but can grow on the su$^+$ssb$^+$ strain was isolated previously (Araki and Ogawa 1981). I tried to isolate a double mutant carrying both *up2* and other amber mutation such as *am3* or *am5*, but it was hard to get. On the other hand, T7 J27a strain (Studier 1981) which produced mutated ssb protein grows normally on *E.coli* 594ssb$^-$ mutant strain. These results brought us to suspect that there were other mutations in *up2* strain. To remove the others mutation(s), genetic cross experiment were carried out between *up2* and wild type T7 phage. The crossed phages were selected on Q1 and 594. The progeny phage that can grow on Q1 but not on 594 was obtained by this experiment. This indicated that *up2* has other mutation(s) rather than gene 2.5. This phage which is dependent on suppressor but not on bacterial ssb was named as T7 *op1*.

**Nucleotide sequencing of *op1* mutation:**
The nucleotide sequence of \( \textit{opl} \) mutation was determined. \( \text{T7 opl} \) makes a 10% smaller ssb protein in a molecular weight than wild type T7 ssb protein in a non-suppressive condition. Determination of amino acid composition of \( \textit{opl} \) protein suggested that the mutation site of \( \textit{opl} \) was near the carboxyl terminal region (in preparation of manuscript). Therefore, the nucleotide sequence around the c-terminal region was determined by Maxam and Gilbert method (1979). The determined nucleotide sequence were between \( \textit{Hinfl} \) site at nucleotide 9,824 and nucleotide 9,769 in r-strand and between \( \textit{Alul} \) site at nucleotide 9,824 and nucleotide 9,861 in l-strand (Figure 4, see Materials and Methods). The result showed that \( \textit{opl} \) mutation is change from TGG to TGA on l-strand at nucleotide 9,805, and an opal mutation.

\[ \text{Mapping of outside mutations of ssb gene:} \]

When genetic cross experiments between the \( \textit{up2} \) mutant and other amber mutants, were carried out, various types of plaques (from very small plaques to normal plaques) were observed.

Moreover isolation of a double mutant, \( \textit{up2} \) and an amber mutant in gene 5 was not successful by a genetic cross. Unidentified mutations other than \( \textit{opl} \) mutation in the \( \textit{up2} \) mutant were mapped by \textit{in vitro} gene manipulation. As the other mutations may have no phenotype themselves, there is no way to identify the mutations by genetic cross.

Therefore, I tried to map them by substituting a various regions of the mutant genome with the corresponding regions of wild type phage \textit{in vitro}. The substituted regions in the \( \textit{up2} \) mutant phage DNA were shown in Figure 5. The solid bar shows original \( \textit{up2} \) DNA and open bar shows a substituted region by the \textit{wild type} DNA. The ZEN2 bacteria carrying an opal suppressor and an amber suppressor were transfected with the recombinant DNAs (AS1 to AS10). Obtained recombinant phages were propagated and the plating efficiency of each phage was examined. It was same for recombinant phages AS1, AS2 and AS3 on 594, and was one tenth of that of \( \textit{up2} \) (Figure 5.). AS8 shows slightly reduced efficiency on 594 (0.5 of the frequency with \( \textit{up2} \)). On the other hand, the efficiencies of AS4, AS5 and AS10 (\( \textit{opl} \)) were \( 10^{-5} \) to that of \( \textit{up2} \).
CHAPTER I

These results indicated that up2 had probably two other mutations: one mutation (designated S'1) lies between BglII-1 site and BstEII site (nucleotide 13,517 to 20,065), and the other (designated S'2) lies between BglII-2 and right end (nucleotide 35,931 to 39,936). These two regions corresponded to the map between gene 4 to gene 7 (S'1) and lies between gene 17 to gene 20 (S'2). The plating efficiencies of AS7, which has both S'1 and S'2 mutations, but not op1 mutation, and AS9, which has S'2 mutation alone, were same as that of wild type phage. It means that S'1 and S'2 mutations themselves had no effect on plaque formation. To map two mutations more exactly, their linkage relationship with various genes were examined. T7 op1S'1 am9 was constructed and crossed with double mutants, am1.am5, am1.am6 and am1.am8 respectively, and the progeny phages were plated on an opal suppressor strain, CAJ64. Two hundred am+ progeny of each cross were picked up and were stabbed onto the plates seeded by CAJ64 or 594. In the cross with am1.am5, am1.am6 and am1.am8, 58%, 85% and 69% of progeny phages were able to grow on 594 respectively (Figure 6). If the S'1 mutation locates at the left of the gene 5 or at the right of the gene 8, the frequency of the recombinant phage which can grow on 594 should decrease or increase, in order, am1.am5, am1.am6, and am1.am8, respectively.

The observed frequency, however was the highest in the cross with am1.am6. This result indicated that S'1 was linked to the gene am6 mutation. Next phage op1S'1.am6 phage was isolated by the cross of AS3 phage and am6 phage. This recombinant phage cannot grow on 594, but its plating efficiency on 594su+2 is the same as that of op1S'1 on 594. If S'1 mutation was in gene 6, op1.S'1.am6 should have a double mutation in the gene 6. Therefore, op1S'1.am6 could not make suppressible protein of the gene 6 for op1 mutation in 594. To test this possibility T7 op1 and op1S'1.am6 were simultaneously spotted onto 594 loan. The complementation did not observed between them. However, when a complementation experiment was carried out using op1S'1.am5 or op1S'1.am8 instead of op1S'1.6am, it was successfully observed (Table 4). These results indicated that S'1 was located in gene 6. By the similar procedure to the above, I ascertained that S'2 was located in gene 18 (Table 4).
Plating efficiency and the burst size of op1 mutant with or without the suppressor mutation:

The plating efficiency of op1 mutant with or without the S⁻¹ or S⁻² mutation is shown in Table 5. For op1 phage as well as 594ssb⁻¹ and 594ssb⁻¹13, it was 10⁻⁵ on 594 as compared with that on CAJ64. On the other hand, on FTP1327 which inserts Gly at the opal mutation site, the plating efficiency of op1 was 0.8, but on 594su⁺²op which inserts Gln at the opal mutation site, it was 10⁻⁴. These results showed that defect of op1 mutation was not substituted with the host ssb gene. The effect of S⁻¹ and S⁻² to the op1 mutation was additive. Plating efficiency of op1S⁻¹ (up2 without S⁻¹ suppressor) was 0.1, and that of op1S⁻² (up2 without S⁻²) was 0.5. Interestingly, phages showed also a cold sensitive character. This is same for T7 up2 phage. On ssb deficient bacterial strains (ssb⁻¹ and ssb⁻¹13), up2, op1S⁻¹ and op1S⁻² had the same very low plating efficiency. It suggested that the suppressor ability of the S⁻¹ and S⁻² mutation to the op1 is dependent on the bacterial ssb function. In other word, T7 wild type phage does not use bacterial ssb in its growth cycle, and by bearing two suppressor mutations, T7 phage turns to be able to utilize bacterial ssb as well as own ssb.

Sedimentation analysis of intracellular T7 DNA:

Since the gene 6 product and gene 18 product are concerned with the formation and breakage of concatamer (Miller and Marion 1976), the effects of S⁻¹ and S⁻² to concatamer formation were examined. Concatamer formation was analyzed by sucrose gradient centrifugation. The results were shown in Figure 7. In wild type infected cells, almost all [³H]-labeled intracellular DNA cosedimented with [³²P]-labeled unit length T7 DNA added as a reference (Figure 7-(a)), and in op1S⁻¹ or up2 infected cells, [³H]-labeled intracellular DNA sedimented broadly but their peaks were coincident with marker DNA (Figure 7-(b),(c)). On the other hand, in op1S⁻², several peaks were observed and sedimented far more faster than the reference DNA (Figure 7-(d)). This means that in the T7 op1S⁻² phage infected cells newly synthesized T7 DNA were hard
CHAPTER I

to process to the unit length. It suggested that the combination of the mutated gene 6
exonuclease (S-1) and mutated ssb (opl) recovered the ability of processing of the
concatemer DNA.

The effect of S-1 and S-2 to ts2.5 and am2.5-2:
T7 opl was able to grow on su' strain, 594 if it carried additionally two other
mutations, S-1 in gene 6 and S-2 in gene 18. I examined the effect of those
suppressors. S-1 and S-2 were introduced to T7 ts2.5 and am2.5-2 by in vitro gene
manipulation. Neither ts2.5S-1S-2 nor am2.5-2S-1S-2 mutant was able to grow on
594 at 42°C, or at 37°C (Table 3.) These results suggested that bacterial ssb cannot
substitute for other T7 ssb mutations than opl even if the mutations S-1 and S-2 were
present.

Mutant ssb proteins in gel electrophoresis:
The mutant ssb proteins, of opl and ts2.5 were analyzed by SDS gel electrophoresis.
T7 opl and ts2.5 mutant phages made a smaller ssb polypeptide than wild type as
expected (Figure 8.).

T7 opl has an opal mutation, and in non-suppressive host it was expected to make
smaller peptide with molecular weight 24,000 than wild type peptide, 25,562.

Although ts2.5 peptide is expected to migrate as same as opl peptide in size, it
migrated slower than opl peptide. The change to Ser at Gly144 in ts2.5 peptide
probably affects the mobility in the gel electrophoresis.

DNA synthesizing ability of the T7 ssb mutants:
The incorporation of [3H]-thymidine to the newly synthesized DNA in T7 ssb mutant
infected cells were examined under no permissive condition. The results were shown in
Figure 9. At 32°C and 37°C, opl, J27a, which was a gene 2.5 mutant isolated by Studier
(1981) and ts2.5 infected cells incorporated [3H]-Tdr less than wild type phage infected
cells (Figure 9 (a),(b)). Incorporation of [3H]-Tdr in opl infected cells was recovered
by the presence of bacterial opal suppressor (Figure 9 (d)). J27a phage did not synthesize DNA at any temperature (Figure 9 (a)-(c)), and on any bacterial strain carrying suppressors (amber and opal) (Figure 9 (d)).

Both am2.5-1 and am2.5-2 phages could not synthesize DNA in a suppressor free strain, WD00, but synthesize DNA about a half amount of DNA synthesized in wild type phage infected cells (Figure 9 (e)). On the other hand, at 42°C ts2.5 infected cells incorporated [3H]-Tdr as well as wild type infected cells after 10 min time lag (Figure 9 (c)). This DNA synthesis in ts2.5 at 42°C is probably abnormal or uncontrolled. The reason is as follows: generally the synthesized DNAs of T7 phage in the phage infected cells were several times longer than unit length (concatemeric DNA). These concatemeric DNAs were processed by maturation proteins coded by the gene 18 and the gene 19. If T7 single-stranded DNA-binding protein is involved in this step, the concatemeric DNA was accumulated in ssb defective strain. The results of sedimentation analysis of newly synthesized DNA supported the above hypothesis (Figure 10). The concatemeric DNAs in the T7 ts2.5 infected cells were not processed and accumulated at 42°C.

UV-sensitivity of mutant phages:

UV-sensitivity of ts2.5 and J27a were measured. Phage ts2.5 was irradiated by UV light at various doses and plated with indicator bacteria after appropriate dilution. The plates were incubated at 32°C for 30 min and some plates were transferred to 42°C and remaining plates were kept at 32°C as control. For phage J27a, the plates were incubated at 37°C. The results were shown in Figure 11. Phage ts2.5 was 1.5 times as sensitive as wild type at 42°C, whereas at 32°C both have equal sensitivity to UV light (Figure 11 (a), (b)). J27a was also 1.5 times as sensitive as wild type to UV irradiation (Figure 11 (c)).

Recombination ability of T7 ssb mutants:
Recombination frequency between gene 6 and gene 19 was measured using ssb mutant phages, ts2.5, am2.5-1 and am2.5-2 (Table 6.). The mutant ts2.5 could carry out recombination at 32°C as well as wild type (about 25%). At 42°C, however it reduced the frequency to about 1/3 of that of wild type. Both am2.5-1 mutant and am2.5-2 mutant also reduced the frequency similarly under nonpermissive condition. These results showed that ssb protein participated in genetic recombination. In the case of the opf mutant, the burst size under the nonpermissive condition was very low, and the high recombination frequency obtained might result from revertant phages.

Formation of intermediate DNA molecules in recombination:

The recombination intermediate DNA molecules were isolated by CsCl density gradient centrifugation (Tsujimoto and Ogawa 1977). Bacteria, 594 were infected with [32p]-labeled T7 ts2.5 phage and [3H]BU-labeled T7 ts2.5 phage at 32°C or 42°C. The phage infected cells were incubated for 10 min, and DNA molecules were isolated after 3 cycles of freezing and thawing. Then isolated DNA molecules were centrifuged in CsCl density gradient. After the first centrifugation, about 1.5 % and 1.3 % of input [32p]-radioactivity were recovered around half-heavy position at 32°C and 42°C, respectively (data not shown). In the second centrifugation, however about 55 % of radioactivity was recovered at half-heavy position at 32°C, whereas few radioactivity was found at half-heavy position at 42°C (Figure 12). These results showed that the intermediates of recombination were not formed in the ts2.5 infected cells at 42°C.
Discussion

In this paper, three mutants of gene 2.5 of T7 phage were isolated: one was, a temperature sensitive mutant, T7 ts2.5, obtained after NTG treatment to the T7 infected cells; and other two were amber mutants, T7 am2.5-1 and am2.5-2, which were obtained by in vitro mutagenesis.

All these mutants could not make viable progeny phage under the restrictive condition, at 42°C or in suppressor free host bacteria. This means that T7 phage sb protein is essential for phage growth, and that bacterial sb protein cannot replace T7 phage sb. These results prompted us to analyze T7 up2 mutant whose growth was dependent on host sb. T7 up2 was found to have an opal mutation opl not but an amber mutation as speculated previously (Araki and Ogawa 1981) in the gene 2.5 by nucleotide sequencing of the mutation. Furthermore, it had additional two suppressor mutations other than the opal mutation in the gene 2.5. One suppressor mutation was in the gene 6; the other was in the gene 18. T7 opl strain which had the opal mutation alone in the gene 2.5 could grow on several host strains such as Q1supE (Signer et al) a derivative from C600 (Appleyard,1954) and W3110 which were believed not to carry an opal suppressor. The analysis of the protein synthesized in the mutant phages infected cells showed that opl phage made an intact size peptide in Q1 as well as in CAJ64 a standard opal suppressor strain, but in 594 a smaller size peptide than wild type. as expected from the mutation site (Araki, Shimizu and Ogawa in preparation of manuscript).

Since the amber suppressor cannot suppress an opal mutation in general, the suppression of opl mutation by the supE strain was seemed to be resulted from the intrinsic ambiguity of tRNAtrp not by the amber suppression. Actually the efficiency of plating of opl strain Q1 was low and about 0.1 to that on CAJ64. The burst sizes of opl strain in these bacterial strains were 5 and 130 respectively. The suppressor ability of Q1 for the opl mutation seems to be as low as an amber mutant on a suppressor free
CHAPTER I

strain, since the burst size of a rigid amber mutant am6 in 594 was nearly one particle/cell.

Growth of T7 up2 strain was dependent on the bacterial ssb gene function (Table 5). This suggested that bacterial ssb play a some role for growth of T7 up2 strain. One explanation is that by the mutations of S'1 and S'2, T7 op1 mutant acquired an ability to utilize able to use bacterial ssb for the growth. The op1 mutant protein complexed with T7 S'1 and S'2 may interact with host ssb to compensate for the defect of the T7 ssb protein. Above explanation was confirmed by the fact that the suppression by the mutations S'1 and S'2 was specific for the mutation op1 and two mutations could not restore the inviability of other T7 ssb mutants (ts2.5 and am2.5-2) under the nonpermissive condition.

This suggests that suppressors probably interact with T7 ssb.

Since the suppressors were the mutations in the gene 6 and gene 18, which participated in the formation and cleavage of concatemers respectively (Miller and Marion 1976; Richardson et al 1987), T7 ssb might be involved in the maturation of T7 DNA by interacting with these genes products.

The ssb protein synthesized by the infection of J27a phage migrated faster than the wild type protein in SDS gel electrophoresis but any bacterial nonsense suppressors could not affect the migration of J27a ssb protein (Studier, 1981), and J27a ssb protein acted in vitro in a manner similar to the wild type protein. J27a phage may have a missence mutation in the ssb gene not but a deletion mutation as speculated (Studier, 1981) and make a full length protein with single amino acids change, since the change of single amino acid in T7 ssb protein could affect the mobility in the gel electrophoresis greatly (Figure 9).

T7 ts2.5 was found to have two mutations: one was a missence mutation, Gly144 to serine; another was a nonsense amber mutation at Trp216. T7 am2.5-1 and am2.5-2 would make 15 amino acids and 200 amino acids peptides, respectively.

The correlation between DNA synthesis (Figure 9-(e)) and progeny formation (Table 3.) by infection of both amber mutants (am2.5-1 and am2.5-2) was reasonable.
However, a large amount of DNA synthesis in T7 ts2.5-infected cells at 42°C (Figure 9-(c)) was unexpected, because T7 ts2.5 could not make viable progeny at 42°C. This discrepancy may be caused by the induction of abnormal DNA synthesis in T7 ts2.5-infected cells at 42°C. In the T7 ts2.5 infected cells, the concatemeric DNAs were accumulated (Figure 10.). This accumulation of the concatemeric DNAs was explained by two ways.

One explanation is that in the late period of T7 wild type phage infection, newly synthesized concatemeric DNAs are processed by the late gene products. In T7 ts2.5 infected cells, however, their processing does not operate at 42°C. The other explanation is that the mode of DNA synthesis in T7 ts2.5 infected cells is different from that in wild type infected cells, and the abnormal molecules such as branched DNA which can not be processed by the T7 late genes are accumulated in ts2.5 infected cells. At present, the former is more likely, because T7 ssb could interacts with the gene 18 product that is concerned with the processing of concatemeric DNA. The gene 18 products probably require T7 ssb function to process concatemeric DNA molecules.

In conclusion, T7 ssb protein is essential for phage growth and it takes parts in several reactions of DNA metabolism such as replication, recombination and repair.


Campbell, J.L., Richardson, C.C. & Studier, F.W. 1987 Genetic recombination and complementation between bacteriophage T7 and cloned fragments of T7 DNA. *Proc.Natl.Acad.Sci.USA* 75: 2276-2280

Dann, J. & Studier, F.W. 1983 The complete nucleotide sequence of bacteriophage T7 DNA, and the location of T7 genetic elements *J.Mol.Biol.* 166: 477-535


Miller, Jr. R.C. & Marion, L. 1976 The role of bacteriophage T7 exonuclease (gene 6) in genetic recombination and production of concatemers *J.Mol.Biol.* 101: 223-234


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Saito, H., & Richardson, C.C. 1981 Genetic analysis of gene 1.2 of bacteriophage T7: Isolation of a mutant of *E.coli* unable to support the growth of T7 gene 1.2 mutant. *J. Virol* 37: 343-351


Legends

Table 3.
The efficiency of plating.

The value was relative to the plaques on 594 of T7 wild type at 37°C.

-: not test  *: small plaque

Table 4.
Complementation Test

The phage listed in row and the phage listed in column were spotted on 594 lawn simultaneously to test the complementation between them.

+: complemented  -: not complemented

Table 5.
Efficiency of plating

Table 6.
Recombination frequency
CHAPTER I

Figure 3.
Mutation sites and diagram of gene 2.5 mutants

(a) mutation sites of gene 2.5 mutants
(b) diagram of mutants

Figure 4.
Mutation site of T7 opI strain in the gene 2.5

DNA fragments containing nucleotides 9,691-9,821 were isolated by polyacrylamide gel electrophoresis and sequenced by the method of Maxam and Gilbert (1979). The nucleotides sequenced were in r-strand from Hinfl site at nucleotide 9,824 to 9,769 and in l-strand from AluI site at nucleotide 9,802 to 9,861. The number of nucleotide and the nomenclature of T7 DNA strands are defined according to Dunn and Studier (1981).

Figure 5.
Mapping of suppressors in T7 up2 by a partial substitution with the wild type strain

Bold lines show the DNA from T7 up2 and open lines show the DNA from T7 wild type. The value of light column of the figure was the relative E.O.P.s of the recombinant phages (AS1 to AS10) to up2 phage at 37°C and was calculated by the following equation:

\[
V(n) = \frac{\text{(plaques of ASn on 594)/(plaques of ASn on CAJ64)}}{\text{(plaques of up2 on 594)/(plaques of up2 on CAJ64)}}
\]

n=1 to 10
Figure 6.
Linkage between suppressor mutation S-1 and amber mutations

T7 opIS-1 am9 was constructed and crossed with double mutants, am1.am5, am1.am6 and am1.am8 respectively, and the progeny phages were plated on an opal suppressor strain, CAJ64. Two hundred am* progeny of each cross were picked up and were stabbed onto the plates seeded by CAJ64 or 594. The value was the ratio of the plaques on 594 to the plaques on CAJ64.

Figure 7.
Analysis of intracellular DNAs in mutants T7 infected cells

E.coli 594 was grown at 30°C to 3x10^8 cells/ml in M9 medium. The Cells were infected with indicated phages at a multiplicity of infection of 10. At 8 min after infection [3H]-thymidine (1.67 GBq/μmol) was added to each infected culture. At 10 min after infection samples were ice chilled with TEN-buffer. The DNA was extracted and analyzed by neutral sucrose gradient sedimentation. After centrifugation the sample was collected from bottom of tubes and acid-insoluble radioactivity was determined. arrow indicates the sedimented position of monomer T7 DNA.

(a) wr  (b) up2  (c) opIS-1  (d) opIS-2
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Figure 8.
Analysis of mutant proteins of ssb

Bacterial strain 594 was grown in M9 medium supplemented with 0.2% Glucose and 0.2% Casamino Acid (Difco) to the density of 3 x 10^8 cells/ml. The culture (5 ml) was irradiated by UV light and after culturing for 5 min, T7 phage was infected at a multiplicity of 20. After 15 min of infection, infected cells were collected by centrifugation at 8000 rpm at 4°C for 10 min. The pellet was suspended in 0.1 ml of SDS buffer. The sample was subjected to SDS gel electrophoresis by Leamli's method. The position of gene 2.5 product was deduced by the position of purified ssb protein which was electrophorized simultaneously.

lane (a): wild type  lane (b): ts2.5  lane (c): am 6  lane (d): op1

The upper arrow shows the position of wild type ssb protein, which identified by purified ssb protein. The lower arrow shows the position of op1 protein.

Figure 9.
Measurement of DNA synthesis

Bacterial strains WD00 or CAJ64thyA was grown to the density of 3 x 10^8 cells/ml in M9 medium supplemented with 0.2% Glucose, 0.2% Casamino Acids, 2 µg/ml thymine and 1 µCi/ml [3H]-thymidine Phages were infected to each culture at a multiplicity of 10.

At a time indicated, 100 µl-samples were removed and equal volume of 10% TCA was added to the samples and chilled on ice and the acid-insoluble radioactivity was determined.

(a): (○) wr (●) op1 (▲) J27a (▲) ts2.5 in WD00 at 32°C
(b): (○) wr (●) op1 (▲) J27a (▲) ts2.5 in WD00 at 37°C
(c): (○) wr (●) op1 (▲) J27a (▲) ts2.5 in WD00 at 42°C
(d): (○) wr (●) op1 (▲) J27a (▲) up2 in Q1sup71 at 37°C
(e): (○) wr in WD00 (○) am2.5-1 in WD003 (●) am2.5-1 in WD00
(▲) am2.5-2 in WD001 (▲) am2.5-2 in WD00

34
Figure 10.
Analysis of intracellular DNAs of T7 ts2.5 infected cells

*E.coli* 594 was grown at 30°C to 3x10^8 cells/ml in M9 medium.
The Cells were infected with indicated phages at a multiplicity of infection of 10. At 8 min after infection [^3H]-thymidine (1.67GBq/μmol) was added to each infected culture. At 10 min after infection samples were ice chilled with TEN-buffer. The DNA was extracted and analyzed by neutral sucrose gradient sedimentation. After centrifugation the sample was collected from bottom of tubes and acid-insoluble radioactivity was determined. arrow indicates monomer T7 DNA.

(a): sedimentation pattern at 32°C
(b): sedimentation pattern at 42°C
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Figure 11.
UV sensitivity of ssb mutants

Phage stocks were diluted to $10^9$ phages/ml in T7 buffer and irradiated in a 100 mm Petri dish with constant agitation under UVS 15-watt low-pressure germicidal lamp at dose rates of about $1.0 \text{ J m}^{-2} \text{ sec}^{-1}$. Irradiated samples plated were incubated under dark room to avoid photoreactivation.

(a): ts2.5 at 32°C (b): ts2.5 at 42°C (c): J27a at 32°C

Figure 12.
Recentrifugation profile of T7 DNA

Centrifugation was carried out by the procedure described in Materials and Methods.

(a): infected at 32°C (b): infected at 42°C
### Table 1.

**E.coli K12 strains**

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Table 2.

T7 phage strains used in this study

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Table 3.

Efficiency of Plating

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<tr>
<td>op1</td>
<td>1 1 10(^{-4}) 10(^{-4})</td>
<td>10.4 - -</td>
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<td>J27a</td>
<td>1 1 0.9 0.8</td>
<td>0.9 - -</td>
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<td>10(^{-5}) 0.8 1</td>
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<td>$opl^{-1}S^{+}2am5$</td>
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<td>-</td>
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<tr>
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### Table 5.

**Efficiency of Plating**

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<th>Q1</th>
<th>594</th>
<th>594 (32°C)</th>
<th>594ssb-1</th>
<th>594ssb-113</th>
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<td><strong>Wild type</strong></td>
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<td>1</td>
<td>0.7</td>
<td>1.6</td>
<td>1.5</td>
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<tr>
<td><strong>up2</strong></td>
<td>1</td>
<td>1</td>
<td>0.8</td>
<td>10⁻²</td>
<td>10⁻³</td>
<td>10⁻⁴</td>
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<tr>
<td><strong>op1</strong></td>
<td>1</td>
<td>0.5</td>
<td>10⁻⁵</td>
<td>10⁻⁵</td>
<td>10⁻⁵</td>
<td>10⁻⁴</td>
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<tr>
<td><strong>op1.5⁻¹</strong></td>
<td>1</td>
<td>-</td>
<td>0.1</td>
<td>5x10⁻³</td>
<td>10⁻³</td>
<td>10⁻⁴</td>
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<tr>
<td><strong>op1.5⁻²</strong></td>
<td>1</td>
<td>-</td>
<td>0.5</td>
<td>10⁻⁴</td>
<td>10⁻³</td>
<td>10⁻⁴</td>
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<tr>
<td><strong>am6</strong></td>
<td>10⁻⁶</td>
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<td>10⁻⁶</td>
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### Table 6.

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<td>burst size</td>
<td>rec. freq.</td>
<td>burst size</td>
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<tr>
<td></td>
<td>%</td>
<td></td>
<td>%</td>
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<td>27.5</td>
<td>120</td>
<td>18.6</td>
<td>60</td>
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<tr>
<td>(am6 x am19)</td>
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<td><strong>up2</strong></td>
<td>27.1</td>
<td>50</td>
<td>4.2</td>
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<tr>
<td>(up2 am6 x</td>
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<td>up2 am19)</td>
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<td><strong>op1</strong></td>
<td>22.5</td>
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<tr>
<td>(op1 am6 x</td>
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<tr>
<td>op1 am19)</td>
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<tr>
<td><strong>ts2.5</strong></td>
<td>29.0</td>
<td>45</td>
<td>5.3</td>
<td>2.1</td>
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<tr>
<td>(ts2.5 am6 x</td>
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<td>ts2.5 am19)</td>
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<tr>
<td><strong>am2.5-1</strong></td>
<td>20.1</td>
<td>47</td>
<td>5.6</td>
<td>1.5</td>
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<tr>
<td>(am2.5-1 am6 x</td>
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<td>am2.5-1 am19)</td>
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<tr>
<td><strong>am2.5-2</strong></td>
<td>22.0</td>
<td>60</td>
<td>7.0</td>
<td>1.6</td>
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<tr>
<td>(am2.5-2 am6 x</td>
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<td>am2.5-2 am19)</td>
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</table>
Figures

Structure of M13mp18bb

Figure 1.
Scheme for mutagenesis of gene 2.5

Figure 2.
CHAPTER I

Mutation sites and diagram of gene 2.5 mutants

(a) mutation sites of gene 2.5

\[\text{(Eco811)}\]

1
ATGGCTAAGAGATTTTCCACCTCTCCTGCCGCTGTTAACCCTACCTCTAGCTTACATCCTAGCC
MetaLyaLysIlePheThrSerAlaLeuGlyThrAlaGluProTyrAlaTyrIleIle

**am2.5-1**

21
AAGCACGACTACGCAGAAGAGAGCCGTTGATTTGGAACCTCCTAAGTTGCTATAAAGC
LysProAspTyrGlyAsnGluGluArgGlyPheGlyAsnProArgGlyValTyrLysVal

41
GACGCTACTATTTCCACACAAAGAGCCGTCGTTCCAGATGCTATGACATGCCATGG
AspLeuThrIleProAsnLysAspProArgCysGlnArgMetValAspGluIleVal

61
TGTACAGAGAGCTATATGCTGCTGCCCTGAGGAAATACAGCTAAATCCACTCCTGCTGTA
CysTyrGluGluAlaTyrAlaAlaAlaValGluTyrGluAlaAsnProProAlaVal

81
GCTCGTGTTAAGAAACCGCTGAACGGTATGAGGTGATGACATGCGCTTGTTCTCCTAGAAG
AlaArgGlyLysProLeuLysProTyrGlyAspMetProPhePheAspAsnGly

101
GACGCTACTACCTTTTAAAATGCATTTCCACATGCTACGGCTTCTCTCAAGAAGAGGACC
AspGlyThrThrThrPheLysPheLysCysTyrAlaSerPheGlnAspLysLysThrLys

121
GACGCGACGAGCATACTGATCTGTTGCTAGTACACTGCGCTGCTGCTGTAACTGTTCA
GluThrLysTyrIleAsnLeuValValValAspSerLysGlyLysLysMetGluAspVal

141
A(Gly-Ser) ts2.5 150
CAGATTATCCTTGTTGCTTACTAGTTAAATATTTCTCTGCTTCATCAAGTTGG
ProIleIleGlyGlySerLysLeuValValValAspSerLysLeuValValProTyrLysTrp

161
AACACCTGCTAGTTGCAATGGAATTTTGATAGCGAGCGTGTAAACTGCTGCTGCTGCT
AsnThrAlaValGlyAlaSerValLysLeuGlnLeuSerValMetLeuValGluLeu

181
GCTACCTTTGGCGCGCTGAAGAGGATGCGCTGCTGCTGCTGCTGCTGCTGCTGCT
AlaThrPheGlyGlyGluAspAspTrpAlaAspValGluGluAsnGlyTyrVal

\[\text{(EcoT141)}\]

201 AG(Ser-amber) 210
GCTCTGTTTCTGCAAAACGACGCAAGAACACGCGACGAGAAGGTGCGAGACGAC
AlaSerGlySerAlaLysAlaSerLysProArgAspGluSerTrpAspGluAspAsp

**am2.5-2**

221
GAAGAGTCCGAGGACGAGCGAGACGACATCTTAA A(Trp-opal) op1
GluGluSerGluGluAlaAspGluAspGlyPhe*** A(Trp-amber) ts2.5

Figure 3.
CHAPTER I

(b) diagram of mutants

- **wt**: 231 a.a.
- **op1**: 214 a.a.
- **ts2.5**: 214 a.a.
- **am2.5-1**: G→A, 15 a.a.
- **am2.5-2**: 200 a.a.

Figure 3 (cont.).
Mutation site of T7 opl strain of gene 2.5

```
10  20  30  40  50  60
ATGGCTAAGA AGATTTTAC CTCCTGCGGT GGTACCAGT AACCTTAAGC TTACATCGCC
***
70  80  90 100 110 120
AAGCCGCACT ACACCAACGA AGACGGTGCC TTTGGAACC CTGCTGGTGT CTATAAAGTT
130 140 150 160 170 180
GACCTGACTA TTCCCAAACAA AGACCCGCAG TGCCAGCGTA TGGTGCGATGA AATGCCTGAAG
190 200 210 220 230 240
TGTCACGAAG AGGCTTATGCT TGCTGCGGTT GAGGAATACG AAGCTAATTC ACCTGCTGTA
250 260 270 280 290 300
GCTCGTGCTA AGAAACCGCT GAAACCGTAT GAGGGTGACA TGCCTGTTCTT CGATAACGGT
310 320 330 340 350 360
GACGGTACGA CTACCTTTAA GTTCAAAATGC TACGCTCTTT TCCAAGACAA GAAGACCAA
370 380 390 400 410 420
GAGACCAAGC ACATCAATCT GTGTTGCTTT GACTCAAAGAG GTAAGAAGAT GGAAGACGTT
430 440 450 460 470 480
CCGATTATCG GTGGTGCTCT TAAGCTGGAATT GTTAAATATT CTCTGTTTCT ATACAAGTGG
490 500 510 520 530 540
AACACTGCTG TAGGGTGCGAG CTGTAAGCTG CAACTGGAAT CCTGATGCTT GGTCGAACTG
550 560 570 580 590 600
GCTACCTTTG GTGGCGGTGA AGACGAATTG GCTGACGAGA TTGAAGAGAA CGGCTATGTT
610 620 630 640 650 660
GCCTCGTGGT CTGCCAAAGGC GAGCAAAACA CGCGACGAA AAGCTTGGGA CGAAGACGAC
AluI | A (opal, op1)
670 680 690 699 ...
GAAGAGTCCG AGGAAGCAGA CGAAGACGGA GACTTCTAA
HinfII

Figure 4.
```
CHAPTER I

Mapping of suppressors in T7 up2 by a partial substitution with the wild type strain

---

Figure 5.
Linkage between suppressor mutation $S^{-1}$ and amber mutations

<table>
<thead>
<tr>
<th>Marker</th>
<th>Value</th>
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<tbody>
<tr>
<td>am5</td>
<td>0.58</td>
</tr>
<tr>
<td>am6</td>
<td>0.95</td>
</tr>
<tr>
<td>am8</td>
<td>0.68</td>
</tr>
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</table>

Figure 6.
Analysis of intracellular DNAs in T7 mutants infected cells

Figure 7.
Analysis of mutant proteins of ssb

Wt ts 6amOP-1

Figure 8.
Measurement of DNA synthesis

Figure 9.
Figure 9. (cont.)
Figure 9. (cont.)
Analysis of intracellular DNAs of T7 ts2.5 infected cells

Figure 10.
UV sensitivity of ssb mutants

Figure 11.
Recentrifugation profile of T7 DNA

Figure 12.
CHAPTER II

Regulation of gene 2.5 expression
CHAPTER II

Abstract

Gene 2.5 of T7 phage locates in the class II transcriptional legion of T7 genetic map, and the mRNA that is transcribed from φ2.5 promoter covers mRNAs for gene 2.5, 2.8, 3 and 3.5.

Gene 3.5 product is lysozyme and is necessary for DNA replication. T7 lysozyme can bind to T7 RNA polymerase and inhibit its activity.

I suppose that a certain mechanism of regulation for φ2.5 operon should exist, otherwise, the expression of gene 3.5 at early stage of infection represses the expression of other gene products.

The products of gene 2.5, 3 and 3.5 are ssb, endonuclease and lysozyme respectively, but the activity of gene 2.8 is not known yet. So I attempt to isolate the mutants of gene 2.8 by in vitro mutagenesis. Two mutants were isolated, and am2.8-I bore the amber mutation near the N-terminal of the peptide and am2.8-2 had the amber mutation near the C-terminal of the peptide.

The plating efficiency of am2.8-I was partially recovered by the presence of cloned gene 1 which was the gene for T7 RNA polymerase, and am2.8-2 could not complement with op1 and am3.

I also discussed the homology of gene 2.8 with gene 7.7, and the mechanism of gene expression of T7 phage.
Introduction

The gene expression of bacteriophage T7 was tightly regulated by several mechanisms. The class I genes are transcribed by host RNA polymerase, and then T7 RNA polymerase that transcribed by host RNA polymerase transcribes class II and III genes. In the early stage of expression of class II genes, host RNA polymerase is inactivated by gene 0.7 product (class I) and gene 2 product (class II). The switching of class II and class III gene expression is seemed to be controlled by T7 lysozyme (gene 3.5 product) (Moffat and Studier 1987). T7 lysozyme tightly binds to T7 RNA polymerase and reduced the polymerase activity. By this modification the transcription of T7 genes is shifted from class II promoter to the stronger class III promoters. The expression of T7 lysozyme has to be controlled, since the expression of lysozyme in the early stage of infection causes to shut off the transcription from class II promoters prematurely.

T7 lysozyme mRNA is transcribed from φ2.5 promoter. In the case of bacteriophage T4, regA gene products bind the control region of several mRNAs, and represses the gene expression at translational level (Adari et al. 1985, Winter et al. 1987). T4 regA protein is not similar to T7 gene 2.8 protein at amino acids sequence level but both are very basic peptides (pI of regA protein is 9.8 and that of gene 2.8 protein is 9.1).

On one hand, T4 gene 32 product binds its own ribosomal initiation site (translational operator) of mRNA and thus controls its own synthesis (Hippels et al. 1983). On the analogy of the case of T4 phage, I suppose that some translational repressors exist in T7 phage. Gene 2.8 product is the potential candidate for the repressor.

Furthermore, by the homology search, I found that T7 gene 7.7 product resembled the gene 2.8 product at amino acids level. This is interesting finding to speculate the functions of these genes.
CHAPTER II

Materials and Methods

Buffers and Media:

All buffers and Media which were used in this CHAPTER were described in Materials and Methods of CHAPTER I. All of radioisotopes were purchased from Amersham, Japan.

Enzymes:

Restriction enzymes, T4 polynucleotide kinase and ligation kit were from Takara. Oligonucleotide-directed mutagenesis system (ver.2) was from Amersham. T7 sequencing kit was from Pharmacia.

DNA and Oligonucleotides:

M13mp18 DNA was purchased from Takara. Oligonucleotides (5'-GACTTCCTAGGGGTGTGGGG-3') for am2.8-1 and (5'-GTCTCCCAGTAGACTATTTG-3') for am2.8-2 for in vitro mutagenesis were purchased from Takara.

Bacterial plasmid and phage strains:

All bacterial and phage strains used in this CHAPTER were shown in Materials and Methods of CHAPTER I. Plasmid pTI1219 (Figure 15.) is kindly gifted from Dr. T. Itoh. Plasmid M13mp18bb is described in CHAPTER I.

Isolation of gene 2.8 mutants by oligonucleotide-directed mutagenesis:

The strategy of isolation of gene 2.8 amber mutants is same as that of gene 2.5 in CHAPTER I. The method is described in Materials and Methods of CHAPTER I.
Complementation tests:

Complementation test between mutant phages was carried out by the method described in Studier (1969). Complementation by plasmid carrying gene $I$ was follows; Overnight culture of *E.coli* carrying the pTI1219 plasmid, was diluted by 50 fold into T-broth, and grown to the density of $1 \times 10^8$ cells/ml and IPTG$^*$ was added to the culture to the final concentration of 10mM. After 1 hr, the culture was used for phage titration.

Homology search between data base and product of gene 2.8:

Homology search was carried out using PROSRCH program (MKI).
CHAPTER II

Results

Isolation of gene 2.8 amber mutants:

The same strategy was used for isolation of gene 2.8 amber mutants as gene 2.5 mutants isolation (see Materials and Methods of CHAPTER I.). One was designed to locate at Ser16 (am2.8-1 mutation), and another, at Gln123 (am2.8-2 mutation). The presence of mutation sites of am2.8-1 and am2.8-2 was confirmed by restriction enzyme digestion. Both mutations were designed to create a sensitive site for EcoT141I or AccI. The DNAs of mutants phages were isolated and digested by BclI and BglII, and followed agarose gel electrophoresis then 3204bp fragments were isolated.

The new restriction site created by introducing the mutation within BclI-BglII fragments was checked by EcoT141I (for am2.8-1) or AccI (for am2.8-2) digestion. The mutation sites and the diagram of mutants are shown in Figure 13. The plating efficiency of am2.8-1 or am2.8-2 was shown in Table 6. The ratio of the plating efficiency on su- to that on su+ for both mutants was same as other T7 amber mutants (ca.10^-6 - 10^-5).

Complementation tests:

The complementation test was carried out between the mutant phages which were listed in Table 5. and the am2.8-1 or am2.8-2 mutant phage (Table 7). The results were follows: mutant am2.8-1 made a clear spot with all other mutants except am1 (gene I-19), but am2.8-2 did not make a spot with am2.5-2 or op1 or am3.

Suppression for the defect of am2.8-1 by the presence of the plasmid carrying gene I RNA polymerase:

Mutation am2.8-1 was not complemented with am1, the complementation by plasmid carrying gene I was examined.

The plating efficiency of am1 phage was almost one on su- bacterial carrying the plasmid with the gene I RNA polymerase. Similarly phage am2.8-1 could restore the
plaque forming ability to $2 \times 10^{-3}$ on this su" bacteria carrying the plasmid with gene 1 strain, although its plaque size is very small. In the case of am2.8-2, the plasmid carrying gene 1 did not affect its plating efficiency. (Table 6.). This shows that the defect of the growth of am2.8-1 could be suppressed by the presence of the enough amount of T7 RNA polymerase.

**Homology of gene 2.8 product with gene 7.7 product:**

The homology search of amino acids sequence of gene 2.8 peptide by the PROSRCH program (MKI) revealed that out of 10,000 peptides, one peptide, T7 gene 7.7 product was very similar to this peptide. Sixty five amino acids residues of gene 2.8 products matches to those of gene 7.7 peptide (Figure 14). Gene 7.7 product has 130 amino acids and is basic peptide (pl=9.4), and gene 2.8 product has 139 amino acids and its pl=9.1. Those facts, suggest that both peptides play a same role in the T7 phage. The gene 2.8 locates in the early site of the class II genes and the gene 7.7 locates in the early site of the class III genes. It is likely that the gene 2.8 controls the expression of the class II genes and the gene 7.7 controls the expression of the class III genes.
The two amber mutants of gene 2.8 were isolated by *in vitro* mutagenesis (Figure 13). The *am2.8-1* mutation was designed for the gene 2.8 to create a short 15 amino acids polypeptide (10% size of the whole 2.8 protein), and the *am2.8-2* mutation to create a 122 amino acids polypeptide (88% size of the whole). These mutants showed anomalous properties in the complementation test. The mutant *am2.8-1* could not be complemented with *am1*, whereas the mutant *am2.8-2* was not complemented with *am2.5* or *am3*. However *am2.8-1* recovered the plating efficiency on the restrictive host carrying the gene 1 on a multicopy plasmid, pTi1219. These means that the overproduction of T7 RNA polymerase could overcome an almost complete defectiveness in the gene 2.8.

On the other hand, the overproduction of the product of the gene 3.5, lysozyme, is known to inhibit T7 phage growth severely. This growth inhibition can be overcome by the mutations within the gene 1 (Moffatt and Studier, 1987). Further, a mutation in the gene 1 could relieve the defectiveness of *am2.8-1* (data not shown). Those facts suggested that T7 *am2.8-1* mutation may lead to overproduction of gene 3.5 lysozyme, which inhibits the T7 RNA polymerase activity and that the overproduction of gene 1 RNA polymerase by introduction of the plasmid pTi1219 into the host cells, could recover phage growth partially. The introduction of the plasmid pTi1219 in the host, however, supported neither the growth of T7 *am2.8-2*, nor complementation of *am2.8-2* with *am2.5* and *am3*. This suggested that T7 *am2.8-2* could not make gene 2.5 and gene 3 products normally.

Considering these results, I hypothesized for the function of T7 gene 2.8 product that the gene 2.8 product negatively controls the expression of gene 2.5, 3 and 3.5 which are transcribed as single mRNA, by binding to their mRNA. In the absence of gene 2.8 function by mutation *am2.8-1*, gene 3.5 (perhaps also 2.5 and 3) product will be overproduced by the absence of the negative control to transcript covered with the gene.
2.5, 3 and 3.5 genes. However the \textit{am2.8-2} mutant product probably have an anomalous binding activity and will repress the translation of gene 2.5 and 3 (perhaps also 3.5) tightly (Figure 16).

By their analysis of the synthesized DNA from R9 infected cells in the sucrose gradient centrifugation, North and Molineux (1980) reported on the T7 mutant \textit{R9}, that was defective in early DNA synthesis, and has a mutation between the gene 2 and the gene 3. The profiles of their centrifugation patterns were similar to those of the DNA isolated from 3.5 defective phage infected cells. The \textit{R9} mutation probably in the gene 2.8, and has a similar characteristics to the mutation \textit{am2.8-2}. The mutation may inhibits the expression of gene 3.5. Therefore, the phenotype of the mutant resembles the gene 3.5 mutant.

A rifampicin-resistant RNA polymerase mutant, \textit{RpoB26} of \textit{E.coli}, causes the inhibition of the growth of T7 phage, and the inhibition is due to a higher rate of termination of transcription by the mutant host RNA polymerase before gene \textit{I T7 RNA polymerase} is synthesized at an enough amount. Yeats \textit{et al.}(1981) isolated the T7 mutant which could grow on \textit{RpoB26}. mutant The isolated mutant \textit{HS36} was found to carry a deletion affecting a T7 gene 2.5 and gene 2.8. From this result they suggested that T7 gene 2.5 product (ssb protein) may stimulate the termination of transcription, and that the inactivation of the gene 2.5 product may restore the normal level of the transcription termination. They also suggested that an alternative possibility: the altered gene 2.8 protein may increase the expression level of T7 RNA polymerase indirectly as mentioned above. Figure 15 shows the comparison of DNA sequences of initiation sites for translation of gene 2.8 and gene 3.5. In both sequences, four "AAA" sequences exist at the upstream region of initiation codon. In the case of T4 phage, same feature of sequence is reported in gene 32, and gene 32 protein is known to bind those regions, and control its expression. Furthermore, T4 phage has another regulation factor, \textit{regA} product. The \textit{regA} protein controls several T4 early genes negatively. The \textit{regA} protein binds specifically to target site near the initiation codon (AUG) of mRNA and represses the gene expression at the translational level (Adari
et al. 1985; Winter et al. 1987). If a similar kind of the regulation mechanism of gene expression of T4 phage are available in T7 phage, the following model could be proposed for the gene expression in early stage of T7 phage infection.

When T7 phage DNA is injected into the bacterial cell, by the phage infection, bacterial RNA polymerase start to transcribe the class I genes, and genes 0.3-1.3 products will be produced. The gene 0.7 protein produced will inhibit bacterial RNA polymerase activity, and then T7 RNA polymerase will start to transcribe the class II genes. There are seven promoters in class II genes, and genes 2.5-3.5 are transcribed from former three promoters (ϕ1.5, ϕ1.6 and ϕ2.5). Gene 3.5 protein will tightly bind to T7 RNA polymerase and then the activity of T7 RNA polymerase will be reduced, so that the transcription of T7 genes will be shifted from the class II promoter to the stronger class III promoters. In this process of transcription shift, the expression of gene 3.5 must be repressed until the other class II genes are transcribed sufficiently. The gene 2.8 product may control the expression of the gene 3.5. To confirm this hypothesis, the gene 2.8 protein must be purified and must be examined its binding of this protein to the specific transcript covering the gene 2.5-3.5 directly.

T7 gene 7.7 product was found to be very similar to the gene 2.8 product at amino acids level in this work (Figure 14). Since the gene 2.8 mutants are lethal on the susceptible hosts, the gene 7.7 product cannot complement the defect of the gene 2.8 mutants. However, it probably plays the same role in the T7 phage development. For example, they mutually have different specificity to a binding site on mRNA, and they may regulate the translation of the different transcripts. It will be important to isolate the gene 7.7 mutants and to characterize them for understanding of the role of gene 2.8 protein.

Dann, J., & Studier, F.W. 1983 The complete nucleotide sequence of bacteriophage T7 DNA, and the location of T7 genetic elements *J.Mol.Biol.*166:* 477-535


Inouye, M., Arnheim, N. & Sternganz, R. 1973 Bacteriophage T7 lysozyme is an N-acetylmuramyl-L-alanine amidase *J.Biol.Chem.* 248 7249-7252

Moffat, B. A. & Studier, F.W. 1987 T7 lysozyme inhibits transcription by T7 RNA polymerase *Cell* 49: 221-227

Wiberg, J.S. & Karam, J.D. 1983 Translational regulation in T4 phage development in "Bacteriophage T4" American Society for Microbiology pp193-201

CHAPTER II

*Proc. Natl. Acad. Sci.* 84: 7822-7826

Legends

Table 6.
Plating efficiency of *am2.8-1* and *am2.8-2*

Table 7.
Complementation test between amber phages

(-) means that the plaque did not form.  (+) means that the plaque formed.

Figure 13.
Mutation sites and diagram of gene 2.8 mutants

(a) mutation sites of gene 2.8 mutants
(b) diagram of mutants

Figure 14.
Sequence homology of amino acids between gene 2.8 and gene 7.7

Asterisk(*) shows both amino acids of gene 2.8 and 7.7 are identical, and vertical bar(\(|\)) shows that both amino acids are similar.
CHAPTER II

Figure 15.
Comparison of initiation sites for synthesis of proteins

The sequences of protein initiation sites of gene 2.5 and gene 3.5 was compared. Four 'AAA' sequences exist in the upstream of ATG codon.

Figure 16.
Model for regulation of gene expression by 2.8 protein

(a) In the case of wild type T7 phage: The active 2.8 protein modulates normally the expression of genes 2.5, 3 and 3.5

(b) In the case of T7 am2.8-1 phage: The am2.8-1 mutant protein is defective to modulate the normal expression of gene 2.5, 3 and 3.5, so the overexpression of them occur.

(c) In the case of T7 am2.8-2 phage: The am2.8-2 mutant protein represses tightly the expression of gene 2.5, 3 and 3.5, so the few amounts of them express.
Table 6.

Plating efficiency of *am2.8-1* and *am2.8-2*

<table>
<thead>
<tr>
<th></th>
<th>594</th>
<th>WD001</th>
<th>WD002</th>
<th>WD003</th>
<th>594(pT11219)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>am2.8-1</em></td>
<td>7.2x10^-6</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>2x10^-3(sp)</td>
</tr>
<tr>
<td><em>am2.8-2</em></td>
<td>2.7x10^-6</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>1.1x10^-6</td>
</tr>
<tr>
<td><em>am1</em></td>
<td>4.3x10^-7</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>0.36</td>
</tr>
<tr>
<td><em>am3</em></td>
<td>5.5x10^-6</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>2.3x10^-6</td>
</tr>
</tbody>
</table>

-: not tested, sp: small plaque
Table 7.

Complementation test between amber phages

<table>
<thead>
<tr>
<th></th>
<th>am1</th>
<th>am2</th>
<th>am2.5</th>
<th>am2.8-1</th>
<th>am2.8-2</th>
<th>am3</th>
<th>am3.5</th>
<th>am4-am19</th>
</tr>
</thead>
<tbody>
<tr>
<td>am2.8-1</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>NT</td>
<td>+</td>
</tr>
<tr>
<td>am2.8-2</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>NT</td>
<td>+</td>
</tr>
</tbody>
</table>

NT: not tested
FIGURES

Mutation sites and diagram of gene 2.8 mutants

(a) mutation sites of gene 2.8 mutants

\begin{align*}
EcoT\text{t}4\text{l} & \\
GTTGAAC\text{T}GCGGAGAAAATCTTGAGCGAATCAAGGTTGACCTCCTCTGTTGGAG & \text{AG(Ser-amber)} \\
\text{MetGluLeuArgGluLysIleLeuGluArgIleLysValThrSerSerGlyCysTrpGlu} & \\
\text{am}2.8-1 \\
TGGCAGGCGCTACGAAATACAAAGAGTTACGGGCAGGTGTGCGAGCAATACGGAAAG & \\
\text{TrpGlnGlyAlaThrAsnAsnLysGlyTyrGlyGlnValTrpCysSerAsnThrGlyLys} \\
\text{am}2.8-2
\end{align*}

ValValTyrCysHisArgValMetSerAsnAlaProLysGlySerThrValLeuHisSer

CysAspAspProLeuCysAspAspProGluHisLeuSerIleGlyThrProLysGluAsn

SerThrAspMetValAsnLysGlyArgSerHisLysGlyTyrLysLeuSerAspGluAsp

ValMetAlaIleMetGluSerSerGluSerAsnValSerLeuAlaArgThrTyrGlyVal

\begin{align*}
\text{AccI} & \\
TCCACTGACATGGTAAATAAGGGTCGTCCACACAAGGGGTATAAACTTTTGAGAACGAGAC & \\
\text{SerThrAspMetValAsnLysGlyArgSerHisLysGlyTyrLysLeuSerAspGluAsp} \\
\text{am}2.8-2
\end{align*}

Figure 13.
(b) diagram of mutants

Diagram of gene 2.8 mutants

\[ \text{wt} \quad \text{am2.8-1} \quad \text{am2.8-2} \]

\[ \quad \quad \quad \quad \quad \quad \quad \text{139 a.a.} \quad \text{15 a.a.} \quad \text{122 a.a.} \]

Figure 13 (cont.)
Sequence homology of amino acids between gene 2.8 and gene 7.7

T7 gene 2.8 (1-139)  MW 15,617
T7 gene 7.7 (1-130)  MW 14,737

2.8  MELREKILERIKVTSSGCWEGQATNNKGYGQVWCNTGKVYCHR- V- -MS-NA-PK
     * ** * * **** * * ** | * ** |

7.7  ---------------MEDCIEWTGGVNSKGYGRKW-VN-GKLVTPHRHIYEETYGPVPT
     GSTVLHSCDNPCCNPEHLSIGTPKENDMVNVKGRSHKG- -Y- -KLSDEDVMAIMES
     * |* ***** * * |****|** *** *** ** | *|*|** *
     GIVVMHICDNPJCYNIKHLTLGTPKDNPEDMVTKGRQAKGEELSKKLTSFDVLAIRSS

SESNVSLARTYGVSGQTICDI -RKGRHGRLRR
     * | ** ***** ** * ** |**
     TLSHRSLGELYGVGSTTIRLQRTWRI - - -

*: identical,  |: similar

Figure 14.
CHAPTER 11

Comparison of initiation sites for synthesis of proteins

gene 2.5

CTCGTGTCGTCCTTGTAGCACCAGAATACAGCTCCTATTAGGGAAGACTCCCT
CTGAGAAAACAAACGAAACCATAAGGAGATGTTACATTATGGCTAAAGAGATTCTCACTTC

***

gene 3.5

TTAAGTTTCGCTGAAACCTGATACCTGCTGAAGTGAATAAGGAACCACAAGAGAGGAGGTC
CCTTTGATAGATTTAAAAAGGAAAGGAGGAAAGGAAAGAATAATGGCTCGTGACTGTAAAA

***

Figure 15.
CHAPTER II

Model for regulation of gene expression by 2.8 protein

\[ \begin{array}{cccccc}
\phi & 2.5 & 2.5 & 2.8 & 3 & 3.5 \\
\hline
\text{wild type} & \text{gp2.8} & \text{gp2.8} & \text{gp2.8} & \text{gp2.8} & \\
& \downarrow & \downarrow & \downarrow & \downarrow & \\
& \text{gp2.5} & \text{gp2.8} & \text{gp3} & \text{gp3.5} & \\
& + & + & + & + & \\
\hline
\phi & 2.5 & 2.5 & 2.8 & 3 & 3.5 \\
\hline
\text{am2.8-1} & \text{gp2.8} & \text{gp2.8} & \text{gp3} & \text{gp3.5} & \\
& \downarrow & \downarrow & \downarrow & \downarrow & \\
& \text{gp2.5} & \text{gp2.8} & \text{gp3} & \text{gp3.5} & \\
& + & - & + & + & \\
\hline
\phi & 2.5 & 2.5 & 2.8 & 3 & 3.5 \\
\hline
\text{am2.8-2} & \text{gp2.8} & \text{gp2.8} & \text{gp2.8} & \text{gp2.8} & \\
& \downarrow & \downarrow & \downarrow & \downarrow & \\
& \text{gp2.5} & \text{gp2.8} & \text{gp3} & \text{gp3.5} & \\
& - & - & - & - & \\
\end{array} \]

Figure 16.
CHAPTER III

Isolation and characterization of gene 17.5 mutant
CHAPTER III

Abstract

In the course of isolation of new mutants in gene 2.5, I obtained a mutant of the new
gene, which was complemented with all known mutants perfectly, but partially
complemented with op1 partially. This new mutant was mapped between the gene 17
and the gene 18, so I named it the gene 17.5 according to the rule of the naming of T7
phage mutant. The DNA extracted from this mutant phage infected cells was examined.
The length of the DNA was one fifth size of the monomer T7 DNA.

This result suggests that the processing site is determined by gene 17.5 product, and
in the absence of the product, the imprecise cutting is occurred
The new mutant of T7 phage was isolated by chance when I attempt to isolate the mutants of the gene 2.5. That was selected as the phage which could complement with all T7 mutants except op1. However, the genetic cross experiments with am2 and am3 showed that the mutation (#26) was not located near the gene 2.5. The location of the mutation was determined by the genetic cross with several T7 amber mutants. Those results showed that the mutation was located between the gene 17 and the gene 18, so it was named the gene 17.5. The products of the gene 18 and gene 19, which were located near this mutant, participate to the processing of the concatemers, so the DNA extracted from gene 17.5 phage infected cells was analyzed.
CHAPTER III

Results and Discussion

Characterization of gene 17.5

The Materials and Methods used in this CHAPTER were described in previous CHAPTERS. The results of two or three factor cross of this mutant (#26) with am17 and am18 were shown in Figure 17. The results showed that the new mutation located between gene 17 and gene 18. From the nucleotide sequence of T7 phage (Dann and Studier 1983), gene 17.5 should correspond to the gene identified by this mutant, and should encode a protein with molecular weight of 7391 Dalton. The gene 17.5 had been a predicted one from the analysis of nucleotide sequence of T7 DNA, this isolation of the mutant proved its existence.

In the case of bacteriophage T3, the gene 17.5 encoded lysozyme (lys)(Miyazaki, Ryo, Fujisawa and Minagawa 1978). To test a possibility that the gene 17.5 product of T7 phage is a lysozyme gene, I carried out one-step growth experiments using 594 as a host. The result shows that any difference in the eclipse period and burst size was not observed (data not shown). The sedimentation pattern of DNA synthesized after T7 gene 17.5 mutant infection was examined by sucrose density gradient centrifugation. The results were shown in Figure 18. As comparison, DNA extracted from the gene 18 mutant infected 594 cells as well as DNA from wild type phage infected cells were analyzed similarly. As expected, DNA from gene 18 mutant infected cells was sedimented as concatemers, and DNA from wild type infected cells, as monomers (Figure 18-(c), Figure 7-(a)). On the other hand, DNA from the gene 17.5 mutant phage infected 594 cells was one fifth size of monomer length (Figure 18-(a)). When DNA was extract from the gene 17.5 infected 594su+2 cells, the sedimentation pattern is similar to that of wild type (Figure 18-(b)). The participation of the product of gene 17.5 to the maturation was not obvious, but one possibility is that the processing site was determined by gene 17.5 product, and in the absence of the product the imprecise cutting was occurred.
However the possibility that the DNA in the gene 17.5 infected cells were more sensitive to bacterial or phage nucleuses than that in wild type infected cells, so it was digested randomly. The recombination frequency of gene 17.5 mutant was also measured, but apparent difference from the frequency of the wild type was not detected. The relationship between gene 2.5 and gene 17.5 is not known now yet, but gene 17.5, 18, 19 and 2.5 products may function together in the course of processing of concatemer DNA.
Dann, J. & Studier, F. W. 1983 The complete nucleotide sequence of bacteriophage T7 DNA, and the location of T7 genetic elements. *J. Mol. Biol.* **166**: 477-535


Legends

Figure 17.
Genetic mapping of #26.

Cells of *E. coli* 594 were grown at 32°C in T-broth to 2x10^8 cells/ml. Cells were infected with two mutants phages at multiplicity of infection of 10 each. They were diluted by 10^4 fold after 5 min of infection. The cells were incubated further for 60 min and chloroform was added to the cells. Map distance (A) was given as following equation:

\[
A = 2 \times \frac{\text{plagues on nonpermissive host}}{\text{plagues on permissive host}}
\]

Figure 18.
Analysis of intracellular DNAs of T7 #26 infected cells

Method was described in legends in Figure 10 of CHAPTER I.

(a): #26 in 594  (b): #26 in 594su^2  (c): *amI8* on 594

The arrow indicates the position of monomer T7 DNA.
Genetic mapping of #26.

<table>
<thead>
<tr>
<th>cross</th>
<th>recombination freq</th>
</tr>
</thead>
<tbody>
<tr>
<td>#26 x am17</td>
<td>1.1%</td>
</tr>
<tr>
<td>#26 x am18</td>
<td>3.3%</td>
</tr>
<tr>
<td>am17 x am18</td>
<td>3.7%</td>
</tr>
<tr>
<td>#26 x am17am18</td>
<td>0.5%</td>
</tr>
</tbody>
</table>
Analysis of intracellular DNAs of T7 #26 infected cells

Figure 18.
Figure 18 (cont.)
Conclusion

In this study, I showed the followings about T7 gene 2.5. (A) T7 phage single-stranded DNA-binding protein is essential for phage growth, especially for DNA recombination and DNA synthesis. The null mutant of T7 ssb gene (am2.5-1) could not synthesize DNA and was defective in recombination on the su- host, whether or not the host has wild type ssb gene. (B) T7 ssb probably interacts physically with several T7 gene products. The first isolated mutant in T7 gene 2.5 up2, had two additional mutations outside the gene 2.5. One of the mutations located in the gene 6, and the other mutation located in the gene 18. It was reported that T7 ssb enhanced T7 exonuclease activity (1,2). Moreover the interaction of gene 2.5 protein with the T7 DNA polymerase and the gene 4 protein was reported previously (3,4). In this work, I showed that T7 ssb interacted with T7 exonuclease (gene 6 product) and the gene 18 product by genetical method. From this work, the following model for interaction between T7 ssb and T7 exonuclease or the gene 18 product can be proposed.

Wild type T7 ssb could enhance the activities of T7 exonuclease and the gene 18 product, but mutated ssb (opl protein) could not. However, when two additional By the mutations, S-1 and S-2 occurred in this opl mutant, T7 exonuclease and the gene 18 product could be enhanced by bacterial ssb instead of T7 ssb.

The S-1 and S-2 had no effect on other T7 ssb mutants (am2.5-2 and ts2.5). Those results may be explained as follows: T7 phages, am2.5-2 and ts2.5 should loss the other activities which opl mutation still held, for example, the interaction with T7 DNA polymerase or the gene 4 primase, so S-1 and S-2 mutations could not support that defectiveness. In 594 ssb-1 and 594 ssb-113 strains, T7 up2 phage could not grow because both phage and bacterial ssb were defective. (C) The expression of genes 2.5 and 3.5 is probably regulated by the gene 2.8 product. I also showed that T7 gene 2.5 and 3.5 was controlled by gene 2.8 product. The gene 2.8 product represses the expression of gene 2.5. One mutant, am2.8-1, which was expected to produce a small
15 amino acids polypeptide could not repress the expression of those genes, 2.5 and 3.5, and the gene 3.5 product was overproduced (Figure 16). The gene 3.5 product, lysozyme and inhibited the activity of T7 RNA polymerase (5). Another mutant am2.8-2 which was expected to produce about 90% length of T7 gene 2.8 polypeptide and the product seems to inhibit more severely than wild type product. If so, the expression of the gene 2.5-3.5 will be repressed more tightly. This agreed with the fact that am2.8-2 could not complement op1.
Citations for Conclusion

(1) Roberts, L., Sadowski, P. & Wong, J. 1982 Specific stimulation of the T7 gene 6 exonuclease by the phage T7 coded DNA binding protein *Biochemistry* 21: 6000-6005

(2) Araki, H. Shimizu, K. & Ogawa, H. 1990 in preparation of manuscript


(5) Moffat, B. A. & Studier, F.W. 1987 T7 lysozyme inhibits transcription by T7 RNA polymerase *Cell* 49: 221-227
Abbreviations

1) NTG; N-methyl-N'-nitro-N-nitrosoguanidine
2) TCA; Trichrolo-acetic-acid
3) BU; 5-bromouracil
4) SLS; sodium N-lauroylasrosinate
5) IPTG; isopropylthio-b-D-galactoside
Acknowledgements

The author is sincerely grateful to Professor Hideyuki Ogawa, Department of Biology, Faculty of Science, Osaka University, for his valuable guidance and encouragements, supports and discussions during this work.

The author also thanks Drs. Tateo Itoh, Tomoko Ogawa and Toshihiro Horii of Professor Ogawa's Laboratory for their kind discussions and helpful advice in this work.

The author further wishes to thank Dr. Hiroyuki Araki for his continuous advice and impressive instructions.

The author wishes to express his sincere gratitude to Professors Toshiteru Morita and Kenichi Matsubara for their critical reading of this thesis.

The author would like to thank Mr. Masanori Fujii for his excellent technical supports.

Finally, the author is indebted to Drs. Jinpei Yamashita and Shouzow Fukushima, Radioisotope Research Center, Osaka University, for their encouragement throughout this work.