Evidence of Lysogeny in Derivatives of *Escherichia coli*

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**ABSTRACT**

Frampton, E. W. (The University of Texas M. D. Anderson Hospital and Tumor Institute, Houston), and B. R. Brinkley. Evidence of lysogeny in derivatives of *Escherichia coli*. J. Bacteriol. 90:446–452. 1965.—Exposure of cultures of several thymine-requiring derivatives of *Escherichia coli* strain 15 to radiation [X rays or ultraviolet (UV)] resulted in an increased synthesis of ribonucleic acid (RNA) as measured by the incorporation of radioactive uridine. In addition to radiation, mitomycin C (5 or 25 \(\mu g/ml\)) or growth in the absence of thymine also stimulated RNA synthesis in cultures in which the bulk of RNA synthesis was terminated by a shift-down in growth conditions. RNA purified from X-irradiated bacteria was resolved on columns of methylated serum albumin and yielded an elution profile which appeared similar to RNA synthesized by phage-infected bacteria. Electron microscopic examination of cultures induced to lyse by exposure to UV radiation, or by growth in the presence of 5-bromo-uracil before exposure to radiation (X rays or UV), showed the presence of mostly incomplete phage particles.

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Exposure of cultures of *Escherichia coli* strain 15 to ultraviolet (UV) radiation was reported to induce colicin formation (Ryan, Fried, and Mukai, 1955; Mukai, 1960). Mukai (1960) recognized the possibility that colicin activity in *E. coli* 15 could be caused by the induction of a defective phage, but evidence was lacking that a defective phage was induced in these bacteria.

During a study on the effects of radiation on ribonucleic acid (RNA) synthesis, it was found that exposure of several derivatives of *E. coli* 15 to radiation (X rays and UV) stimulates RNA synthesis. In contrast, X-irradiated cultures of *E. coli* B/r demonstrated an inhibited synthesis of RNA (Frampton, 1964). Initially it was thought that the stimulated RNA synthesis observed in induced cultures of *E. coli* 15 derivatives represented messenger RNA required for colicin production. However, similarities in the type of RNA synthesized by these cultures and by phage-infected bacteria led to an electron microscopic examination of induced cultures for evidence of phage particles. This paper describes some of the properties of the RNA synthesized by X-irradiated cultures and presents electron micrographs of the phage particles found in lysates of several derivative strains of *E. coli* 15.

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**MATERIALS AND METHODS**

**Bacteria and growth conditions.** Four thymine-requiring strains descended from *E. coli* strain 15 were employed in this study. Two of the strains used, *E. coli* 15T− and *E. coli* TAU, are subject to lysis after exposure to UV radiation, whereas *E. coli* 15T− (555-7) and *E. coli* TAU-bar are not. *E. coli* 15T− was grown with aeration at 37 C in medium C (Roberts et al., 1955) supplemented with thymine or thymidine (4 to 20 \(\mu g/ml\)). *E. coli* TAU (strain 15T-A-U+), a polyaxotroph (Kanaiz et al., 1959), was supplemented with thymine (20 \(\mu g/ml\)), arginine (58 \(\mu g/ml\)), and uracil (20 \(\mu g/ml\)). *E. coli* 15T− (555-7) obtained from R. S. Weatherwax and selected for its resistance to lysis after exposure to UV radiation (Weatherwax and Landman, 1960) was supplemented with thymine or thymidine (4 \(\mu g/ml\)), methionine (30 \(\mu g/ml\)), tryptophan (14 \(\mu g/ml\)), and arginine (38 \(\mu g/ml\)). *E. coli* TAU-bar, obtained from P. C. Hanawalt (1963), was supplemented with thymine (20 \(\mu g/ml\)), uracil (20 \(\mu g/ml\)), proline (20 \(\mu g/ml\)), plus methionine, arginine, and tryptophan at the same levels used for *E. coli* 15T− (555-7). Enriched media used in shift-down experiments contained 1% (w/v) Casamino Acids (Difco) in addition to the regular supplements. All liquid media contained 0.2% (w/v) glucose. Membrane filters (Schleicher and Schuell type B-6, 150 mm) were used for media changes and harvesting procedures.

**Irradiation of bacteria.** X irradiation of bacterial suspensions was performed as previously described (Frampton, 1964). UV irradiation, with stirring,
was carried out on 50-ml samples of either unconcentrated or fivefold concentrated washed bacterial suspensions in a sterile petri dish 95 cm from two General Electric germicidal lamps (output 7.5 ergs per mm² per sec). Irradiated bacteria were resuspended at one-half harvesting concentration and incubated at 37°C during the postirradiation period.

**Purification and resolution of RNA.** Cell suspensions (250 ml) were harvested, washed, and resuspended in 10 ml of TM buffer (10⁻² M tris(hydroxymethyl)aminomethane, 10⁻³ M MgCl₂, pH 7.4). Bentonite (1 mg/ml) was added, and the cells were disrupted in a French pressure cell. After clarification of cell extracts at 20,000 X g for 15 min, the RNA was purified with phenol and sodium dodecyl sulfate and precipitated with alcohol, as described by DiGirolamo, Henshaw, and Hiatt (1964). No effort was made to remove the DNA from these preparations. Purified nucleic acid preparations (10 A₂₆₀ units) were applied to columns (9 cm X 2.54 cm²) of methylated serum albumin-coated kieselguhr (MAK) by use of the single-layer modification described by Sueoka and Cheng (1962). A linear gradient (500 ml) of NaCl (0.4 to 1.0 M) in phosphate buffer (pH 6.7) was applied with enough air pressure to give a flow rate of 1.5 ml/min, and 5-ml fractions were collected.

**Measurement of radioactivity.** Samples (3 ml) were removed from the cultures at various times and added to an equal volume of cold 10% (w/v) trichloroacetic acid. After 30 min, the acid-insoluble material was collected on Millipore filters (0.65 μm pore size, 25 mm in diameter). The washed and dried filters were placed in vials containing a solution of phosphor in toluene and counted in a Packard Tri-Carb scintillation counter. The fractions from the MAK column were treated the same way after the addition of bovine serum albumin (0.5 mg) to each tube.

**Induction of lysis in lysis-resistant strains.** Cultures were grown in supplemented minimal media to about 10⁹ to 2 X 10⁸ cells per milliliter, washed free from thymine, and incubated for 40 min in media containing 5-bromouracil (2 μg/ml). The cells were then harvested and washed free from 5-bromouracil before exposure to radiation. E. coli 15T⁻ (555-7) was X-irradiated (10 kr) and E. coli TAU-bar was exposed to UV radiation (400 ergs/mm²) before being returned to thymine-supplemented media and incubated for 2 hr. Absorbancy of these cultures was measured at 420 μm, and lysis was observed within 60 min after irradiation.

**Preparation of material for electron microscopy.** Lysed cultures were centrifuged at 3,000 X g for 15 min, which removed unlysed cells, cell debris, and adsorbed or trapped phage particles. The upper half of the supernatant material was removed with a pipette and centrifuged at 96,572 X g for 2 hr in a Spinco model L-2 preparative ultracentrifuge with a type 50 rotor. Both pellets were gently suspended in unsupplemented growth media.

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**Fig. 1.** Stimulation of uridine-2-C¹⁴ (4 μg per 8 μg per ml) incorporation in cultures of Escherichia coli 15T⁻ (555-7). The following conditions are shown: (a) stimulation in X-irradiated (60 kr) log-phase cells (16 μg/ml), (b) response to varying doses of X rays after a shift-down, (c) effect of mitomycin C (5 or 25 μg/ml) after a shift-down, and (d) effect of thymineless growth after a shift-down.

**Fig. 2.** Resolution of purified RNA on columns of MAK. Uridine-H³ (0.4 μc per 2 μg per ml) was added 16 min after the shift-down and incubation was continued for 16 min. RNA was extracted from: (a) unirradiated Escherichia coli 15T⁻ (555-7), (b) E. coli 15T⁻ (555-7) exposed to 60 kr of X rays, (c) unirradiated E. coli 15 TAU, and (d) E. coli 15 TAU exposed to 60 kr of X rays.
Fig. 3-8. Electron micrographs of cell lysates. (3) Phage in P1 fraction from Escherichia coli 15T-, × 770,000. (4) Dispersed subunits of structures shown in Fig. 5 surrounding almost intact phage in P1 fraction from E. coli 15T-, × 220,000. (5) Globular bodies A, B, C, in P1 fraction from E. coli 15T- showing subunits. × 220,000. (6, 7, and 8) Complete and incomplete particles in P2 fraction from E. coli TAU. × 280,000.
Fig. 9-11. Electron micrographs of cell lysates. (9) Full and empty heads in P₂ fraction from Escherichia coli 15T⁻ (555-7). X 280,000. (10) Tails with contracted sheaths and head in P₂ fraction from E. coli 15T⁻ (555-7). X 280,000. (11) Cluster of tails showing contracted sheaths in P₂ fraction from E. coli TAU-bar. X 280,000.
media. The low-speed pellet was designated as fraction P1, and the high-speed pellet as fraction P2. Suspensions of the P1 and P2 fractions were negatively stained with potassium phosphotungstate according to the procedure of Brenner and Horne (1959). A Hitachi HU 11A electron microscope was used to examine the material.

Chemicals. Mitomycin C and 5-bromouracil were obtained from Calbiochem. Uridine-2-<sup>14</sup>C (28 mCi/m mole) and uridine-<sup>H3</sup> (3 to 4 c/m mole) were products of New England Nuclear Corp., Boston, Mass. Adenine-2-<sup>14</sup>C (1.7 mCi/m mole) was obtained from Volk Radiochemical Co., Chicago, Ill. Sodium dodecyl sulfate, obtained from L. Light and Co. Ltd., Colnbrook, England, was recrystallized from hot alcohol. Crystalline bovine serum albumin from Nutritional Biochemicals Corp., Cleveland, Ohio, was used to prepare the methylated serum albumin.

**RESULTS**

RNA synthesis in induced bacteria. A variety of procedures stimulated RNA synthesis in cultures of *E. coli* 15T<sup>-</sup> (555–7). Postirradiation RNA synthesis was stimulated in bacteria taken from cultures in logarithmic growth and exposed to X rays (Fig. 1a). In cultures in which the bulk of RNA synthesis was terminated by transferring the cells from growth in enriched media to growth in minimal media and defined as a shift-down in growth conditions (Kjeldgaard, Maaløe, and Schaechter, 1958), RNA synthesis increased after exposure to increasing doses of X rays (Fig. 1b). By use of this shift-down technique to assay for the effects of various treatments on the synthesis of messenger RNA (Hayashi and Spiegelman, 1961), it was found that the addition of mitomycin C (5 or 25 μg/ml) or thymineless growth led to an early stimulation of RNA synthesis (Fig. 1c, d). RNA synthesis was also increased in cultures of *E. coli* 15T<sup>-</sup>, *E. coli* TAU, and *E. coli* TAU-bar, which were exposed to UV radiation (200 to 400 erg/mm<sup>2</sup>) before growth under shift-down conditions. Adenine-2-<sup>14</sup>C incorporation was stimulated in cultures exposed to X rays or UV radiation, and thus eliminates the possibility that the observations were specific for uridine.

<table>
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<tr>
<th>Strain</th>
<th>Nutritional requirements</th>
<th>Lysis inducible by UV alone</th>
<th>Lysis inducible by 5-BU+irradiation</th>
<th>Complete plaque in lysates</th>
<th>Incomplete plaque in lysates</th>
<th>Plaques on <em>E. coli</em> B, C, 15T</th>
<th>RNA synthesis increased by induction</th>
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<tr>
<td>15T&lt;sup&gt;-&lt;/sup&gt;</td>
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<tr>
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<td>+</td>
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<tr>
<td>TAU-bar</td>
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<td>+ (UV)</td>
<td>0</td>
<td>+</td>
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* Abbreviations: thy = thymine; arg = arginine; ura = uracil; met = methionine; try = tryptophan; pro = proline; 5-BU = 5-bromouracil.
moucuracil prior to being irradiated. However, many full and empty heads, and tail pieces with contracted sheaths were observed in these preparations (Fig. 9-11). Standard phage assay techniques (Adams, 1959) failed to detect plaque-forming capacity in any of the lysates with E. coli B, E. coli C, and E. coli 15T- as indicator strains and confirmed a previous observation (Mukai, 1960).

A summary of the characteristics of the various strains used in this study along with significant results are compiled in Table 1.

**DISCUSSION**

The major point of interest established in the present paper is that derivatives of E. coli strain 15, whether sensitive or insensitive to lysis after exposure to UV radiation, can be induced to liberate particles morphologically resembling bacteriophage. The bacterial strains enumerated in this investigation are of particular interest because they have been utilized in many recent investigations concerned with macromolecular synthesis. The use of any of these strains in experiments requires, therefore, a consideration of how lysogeny might affect the system being studied.

The absence of plaque-forming phage and the presence of apparently incomplete plaque particles in lysates suggest that a “defective-lysogenic” state (Arber and Kellenberger, 1958) may be responsible for the colicin activity previously described in various bacterial strains derived from E. coli strain 15. The identification of phage particles in lysates, however, does not exclude the possibility that these strains are also colicinogenic. Factors controlling induction appear to be identical in both lyogenic and colicinogenic bacteria (Adams, 1959; Fredericq, 1963). UV radiation and thymineless growth were reported to induce colicin formation in strains derived from E. coli 15 (Makai, 1960; Menningmann, 1964; Luzzati and Chevallier, 1964). Fredericq (1963) suggested that colicins are synthesized by prophage which are so defective that upon induction the only component synthesized is a protein related to a lethal protein located in the tail portion of virulent phage. Obviously the phage particles visualized in electron micrographs shown here are not nearly so defective. This fact may account for the lysis obtained in induced cultures of these strains—a feature not usually observed in colicinogenic bacteria. Epstein et al. (1963) described a variety of defects in phage maturation, and it seems possible that an additional mutation(s) affecting the lytic mechanism may be involved in the lysis-resistant strains E. coli 15T- (555-7) and E. coli TAU-bar. In subsequent studies, the presence of incomplete phage particles was observed in UV-induced cultures of these two strains which were lysed with lysozyme without having been exposed to 5-bromouracil (Frampton and Brinkley, *unpublished observations*). By the negative staining procedure used in this study, there appeared to be more unassembled phage components than complete phage in the lysates of E. coli 15T- and E. coli TAU. Ratios of intact phage to unassembled components, or of heads to tails, were not calculated.

The radioactivity eluting after the 23S RNA peak (Fig. 2d) is similar to observations made after phage infection (Ishihama et al., 1962; Kano-Sueoka and Spiegelman, 1962). Characterization of this RNA was insufficient, however, for us to conclude that it is phage-specific RNA. Increased RNA synthesis in cultures exposed to less disruptive treatments than X rays suggests that alterations in cell permeability or organization are not major factors in the increased incorporation of RNA precursors. Experiments are in progress to characterize the phage and to determine the properties of the phage nucleic acid.

**ACKNOWLEDGMENTS**

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**Addendum**

Subsequent to the completion of the experimental findings presented in this paper, the authors learned of two investigations reporting the presence of defective phage particles in E. coli 15. H. D. Menningmann kindly forwarded to us a copy of a manuscript he submitted for publication describing the presence of a defective phage in lysates of UV-induced cultures of E. coli 15T-; Sandoval, Reilly, and Tandler (1965) recently reported the likelihood that a defective phage is responsible for colicin activity in induced cultures of a prototrophic strain of E. coli 15.

**LITERATURE CITED**


