

Regulatory Mutations for Anaerobic Inducible Gene Expression in *Salmonella typhimurium*

Bang, Iel Soo, Yun Joung Lee, Sang Kyun Koh*, Chung Sun An**,
Yung Nok Lee and Yong Keun Park

Department of Biology, Korea University, Seoul 136-701, Korea

*Department of Microbiology, Taejon University, Taejon 300-716, Korea

**Department of Biology, Seoul National University, Seoul 151-742, Korea

New regulatory loci which participate in the regulation of anaerobic inducible gene expression in *Salmonella typhimurium* were identified. We observed the regulatory network of new regulator mutations to various anaerobic inducible gene (1). Some anaerobic inducible *lac* fusions were also induced at low pH condition which was severe environment to withstand for its virulence at the place like phagolysosome. Six oxygen-regulated regulatory mutants (*oxr*) isolated by Tn10 mutagenesis were divided into two groups. Five of them were found to show negative effect on the regulation of anaerobic gene expression, while one showed positive effect on the regulation. Genetic loci of four *oxr* were identified with 54 Mud-P22 lysogens covering the whole chromosome of *S. typhimurium*, in the nearby region of map unit 87 min (*oxr101*), 63 min (*oxr104*), 97 min (*oxr105*), and 57 min (*oxr106*), respectively. Two *oxr* mutants were subjected to two-dimensional polyacrylamide electrophoretic analysis of anaerobic inducible proteins for searching the control circuitry of our *oxr* mutants.

KEY WORDS □ *Salmonella typhimurium*, *ani-lacZ* fusion, Mud-P22 lysogen oxygen-regulated regulatory mutant.

Bacteria generally respond to various types of physiological stresses including heat shock, ultra-violet irradiation, starvation, pH change, and anaerobiosis (8). *Salmonella typhimurium*, the enteric bacterium, survives successfully during the shift between aerobic and anaerobic growth, and at low pH condition to have virulence. Many gene expressions in this bacteria are controlled by the presence or absence of molecular oxygen. When grown anaerobically, many proteins involved with anaerobic respiration are induced while some proteins involved with aerobic respiration are repressed (9). Using the random *lac* operon fusion technique, many *ani* (anaerobic inducible) and *oxi* (oxygen inducible) genes have been characterized (2, 21).

However, the regulatory mechanism for the oxygen-regulated gene expression has been rarely characterized. The most characterized anaerobic regulatory locus is *fnr* of *Escherichia coli* (5, 11, 13). The *fnr* mutation prevents anaerobic induction of several respiratory enzymes (19, 20, 22). It has been reported in *S. typhimurium*, that several oxygen-regulated regulatory genes (*oxr*) participate in anaerobic transcriptional control. These include

oxrA, homologous loci to *fnr* of *E. coli*, *oxrB*, *oxrC* (*pgi*), *oxrD*, *oxrE* (*earA*), *oxrF*, and *oxrG* (3, 12, 23).

In the previous study, we have constructed and identified 13 *ani-lacZ* operon fusions added to already known 16 *ani-lacZ* fusions in *S. typhimurium* (1). To search for the regulatory loci controlling anaerobic gene expression, we utilized six *ani-lacZ* operon fusions that showed different regulatory characteristics. Recently, there have been the reports about that *S. typhimurium* has an adaptive response to extreme acidic pH condition, which provides an explanation of its survival from this harsh *in vivo* environment like in macrophage phagolysosome (6). So, we checked if our *ani-lacZ* fusions are induced by low pH, looking for commonly responsible genes at both conditions. This report introduces new *oxr* mutations and several acid-inducible *ani-lacZ* fusions, and provides regulatory network about anaerobiosis and pH induction. Finally, we analysed anaerobic inducible proteins of our *oxr* mutant by two dimensional polyacrylamide gel electrophoresis (PAGE) and determined which are controlled by our *oxrs*.

MATERIALS AND METHODS

Strains and bacteriophages

The bacterial strains and bacteriophages used in this study are listed in Table 1. Phage P22HT 105/1-int, and its derivative H5, were used for general transduction and nonlysogen test, respectively.

Media and cultural conditions

Cultural conditions including LB medium, minimal E medium, MacConkey medium, Green plates for phage sensitivity were used as described early (1,2). NCE-lactose minimal medium for spontaneous mutation, MOPS (Morpholine propane sulfuric acid) for labelling with S³⁵-methionine were used. Bochner medium was used for mapping the Tn10 insertions as described by Nicholas *et al.* (18). Decarboxylase base moeller media for identifying amino acid decarboxylase gene were used as described by Auger *et al.* (6). Antibiotics were used at the concentration of 30 µg/ml for ampicillin, 20 µg/ml for kanamycin, 20 µg/ml (complex medium), 10 µg/ml (minimal medium) for tetracycline.

For anaerobic condition, 1 ml of paraffin oil was overlaid to liquid culture and Gaspack Anaerobic system (BBL Microbiology system) was used for plate.

Genetic manipulation

General transduction with P22HT105/1-int was performed as described previously (1,17). After transduction, nonlysogenic strains were identified by cross-streaking against phage H5 on the green indicator plate.

Isolation of regulatory mutants

Two methods were used. The first method used to isolate regulatory mutants involved screening a random pool of Tn10 insertions into regulatory loci (17). P22HT105/1-int propagated on the Tn10 insertion pool randomly inserted into *S. typhimurium* chromosome was plated with *ani-lacZ* recipients onto MacConkey Tc plate. Duplicated plates were incubated aerobically (looking for constitutive expression of β-galactosidase) and anaerobically (looking for a lack of anaerobic induction). The second method involved plating 10⁷ cells of *lacZ* fusion strains onto NCE-lactose medium with incubation under repressive condition (aerobically for *ani-lacZ* strains). This method was used to search for spontaneous regulatory mutations which express constitutively *lacZ* fusion, resulting in β-galactosidase levels suitable to support growth on lactose as a sole carbon source (3).

Effects of isolated regulatory mutants to various *ani-lacZ* fusion strains were analysed by β-galactosidase activity test (17).

Linkage mapping of oxygen-regulated genes

For linkage mapping of our *ani*, *oxi-lacZ* fusions, strains having minitransposon Tn10Δ16Δ

Table 1. Bacterial strains and Bacteriophages

Strain or Phage	Genotype	Source
Strains		
<i>S. typhimurium</i> LT-2	wild type	SGSC ^a
AK3131	<i>zad</i> -3131 (linked 24% to <i>leuBCD</i> by P22)	SGSC
AK3150	<i>zah</i> -3150 (linked 82% to <i>proAB</i> by P22)	SGSC
Mud-P22 Mapping Strains		
YK109	<i>ani</i> 2001::Mu dJ	Our Lab.
YK126	<i>ani</i> 2005::Mu dJ	↗
YK127	<i>ani</i> 2006::Mu dJ	↗
YK130	<i>ani</i> 2009::Mu dJ	↗
YK131	<i>ani</i> 2012::Mu dJ	↗
YK132	<i>ani</i> 2013::Mu dJ	↗
YK211	<i>oxi</i> 3011::Mu dJ	↗
Bacteriophages		
P22	HT 105/1-int	J.W. Foster
H5	Derivative of P22	↗

^aSGSC: Salmonella Genetic Stock Center at Univ. of Calgary, Canada.

17 randomly inserted on the chromosome of *S. typhimurium* (4). Phage P22 HT propagated on our Mu dJ(Km, *lac*) operon fusions were plated with overnight culture of the Tn10Δ16Δ17 known insertion strain onto LBKm. Selected Km^r colony was replicated to LBTC, then cotransduction frequency was calculated by using Kemper's formula (1).

Rapid mapping of *oxr* genes with Mud-P22 prophages

Youderian and colleagues *et al.* (24) constructed a set of map, locked in Mud-P22 prophages (MudP: clockwise, MudQ: counterclockwise) along the *S. typhimurium* chromosome. Each of 54 prophages was able to package about 3 minutes of chromosomal DNA adjacent to the site of prophage insertion. For preparing each lysate of each Mud-P22 lysogens, the procedure of Nicholas *et al.* (18) was used.

oxr mutants carrying the Tn10 to be mapped was grown to 4×10⁸ cells/ml in LB medium containing tetracyclin. The cells were washed twice in phosphate-buffered saline and diluted 10-fold, and 0.1 ml cells were plated on fresh Bochner plates. Each 5 µl spot of 15-fold diluted all the Mud-P22 lysates was applied to prespread Bochner plates. The plates were incubated at 37°C for 24 hr. The Mud-P22 insertion close to the site of Tn10 insertion gave a confluent spots of Tet^r transductants.

Two-dimensional polyacrylamide gel electrophoresis

The procedure for two-dimensional electrophoresis of cellular proteins was as described by Spector *et al.* (3,21). Cells were grown in MOPS medium with vigorous aeration to 2×10⁸ cells/ml. Then cells were labelled with 50 µCi/ml of H₂³⁵SO₄

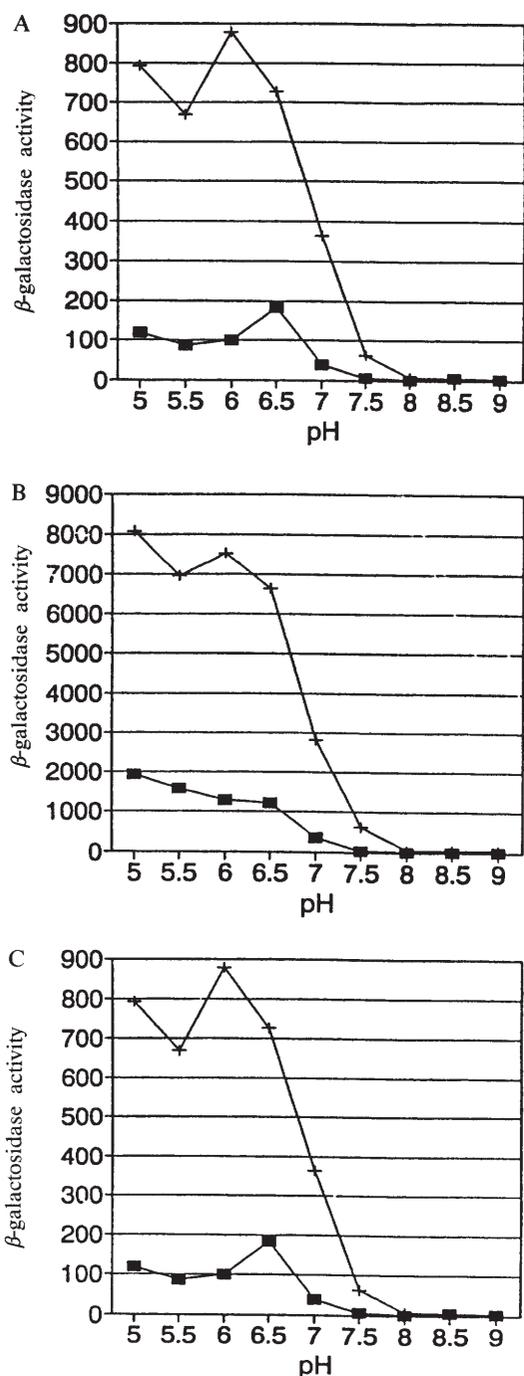


Fig. 1. Transcriptional control of *ani-lacZ* fusion strains by external pH.

(Cells were grown to equivalent densities under aerobic and anaerobic conditions in LB medium containing MES or MOPS buffers) +: aerobic, ■: anaerobic. A: YK126, B: YK131, C: YK132

Table 2. Decarboxylase test of pH regulated operon fusions

Strain	Genotype	Decarboxylase base moeller		
		1% lysine	1% argine	1% ornithine
LT-2	wild type	P	V	P
YK112	<i>ani2004::Mu dJ</i>	P	V	P
YK124	<i>ani2002::Mu dJ</i>	P	V	P
YK125	<i>ani2003::Mu dJ</i>	P	V	P
YK126	<i>ani2005::Mu dJ</i>	P	V	P
YK131	<i>ani2012::Mu dJ</i>	Y	V	P
YK132	<i>ani2013::Mu dJ</i>	P	V	P

P: purple, V: violet, Y: yellow

and split: 2 ml of cells were left under continuous aerobic culture and the other 2 ml were transferred to culture tube and overlaid with paraffin oil, then grown for one generation time.

About 1.5 ml of labeled cells was pelleted and suspended in 13 μ l of sodium dodecyl sulfate (SDS) lysing solution. They were boiled for 5 minutes and run in a pH 5 to 7 isoelectric focusing system followed by 11.5% SDS-PAGE. Comparisons were made between aerobic and anaerobic samples with equivalent protein (5~15 μ g) at the base on the coordinates of standard two-dimensional profiles of *S. typhimurium* made by Spector *et al.* (21).

RESULTS AND DISCUSSION

Effect of the external acidic pH to *ani-lacZ* fusion strains

External pH has been implicated as a signal in a growing number of genetic responses including the pathogenesis in some enteric bacteria. Sometimes they encounter both anaerobic and low pH conditions as well as other harsh stresses to overcome for their virulence (15). To observe the effect of pH change on the anaerobic gene expression, all *ani-lacZ* fusion strains we've got were challenged to a wide range of pH (Fig. 1). Some of them, YK126, YK131, and YK132, also showed high induction fold of β -galactosidase activity at the external acidic pH condition (Fig. 1). Because it has been known that several amino acid decarboxylase genes were induced under anaerobic conditions at low pH (6,7), the above fusion strains were subjected to decarboxylase indicator media in order to verify amino acid decarboxylase gene deficiency (Table 2). Only YK131 showed lysine decarboxylase deficiency, and the other strains were not related to decarboxylase genes. The result obtained so far indicated that there is another gene group or modulon for induction at both anaerobic and low pH con-

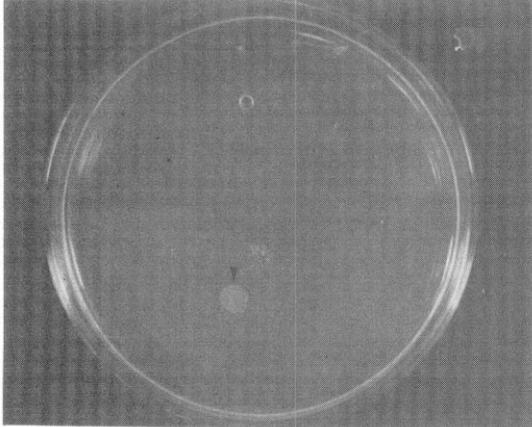


Fig. 3. Rapid Mapping of *oxr101::Tn10* mutation by Mud-P22 lysates. The lysates were diluted 15-fold and 5- μ l volumes were spotted as described in Materials and Methods. Arrowhead indicates confluent spots where Tn10 was exchanged by one of Mud P22 prophages.

was controlled by several regulator (e.g. *tppB*, *tppR*, *oxrC*) (3, 12, 23). Therefore, our *oxr* mutations introduced to other *ani-lacZ* fusions different from parent *ani-lacZ* strain, but our *oxr* mutation did not affect to other *ani-lacZ* strains (data not shown).

And the more we examined the effect of our *oxr* mutants at the external acidic pH condition, any *oxr* strain was not coregulated with low pH. Although there was coregulator with both anaerobic and low pH condition like *earA* (3), our *oxr* participated only in oxygen regulation. The regulator mutation *oxr106*, for YK132 which induced at both anaerobic and low pH, did not show any difference at the acidic pH condition. These results showed that there was more *oxr* gene than known *oxrs* and regulatory pathway would be more complexed, not formulated as described previously (2, 3).

Rapid mapping of Tn10 insertions into *oxr*

To map the regulatory loci, we used recently constructed the P22/Mu hybrid phage, Mud-P22 prophages, packaging the chromosome of *S. typhimurium* on both transcriptional direction. If the homologous recombination between Tn10 insertion near *oxr* region and one of 54 Mud-P22 lysates occurred, Tn10 could be exchanged by Mud-P22. Then *oxr* Tn10 strain is to Tet^r transductant and represents confluent spot on Bochner's media, while the remaining spots appeared similar to the background of cells that did not receive any phage (Fig. 3). By using this method, newly isolated *oxr* mutation mapped in the region of map unit 86 min for *oxr101*, 63 min for *oxr104*, 97 min for *oxr105* and 57 min for *oxr106*, respectively (Fig. 2). These loci were revealed to new loci of *oxr* mutation compared to already

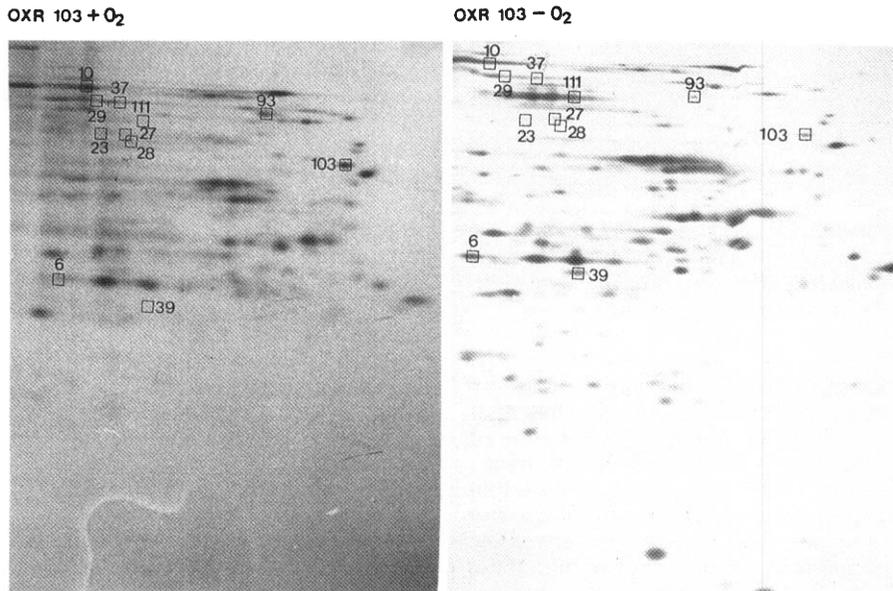


Fig. 4. Two-dimensional patterns of anaerobiosis-inducible proteins from *oxr103* mutants. SDS-boiled lysates were prepared as described and run in a two-dimensional system including a pH5 to 7 (right to left) isoelectric focusing gel followed by 11.5% SDS-PAGE. Acidic proteins are situated to the right of each gel.

Table 4. Effects of various regulatory mutations on the two-dimensional profile of anaerobiosis-inducible proteins

Protein no. and designation ^a	Induction ^b						
	<i>oxr103</i>	<i>oxrA</i>	<i>oxrB</i>	<i>oxrC</i>	<i>earA</i>	<i>oxrF</i>	<i>oxrG</i>
6.ANI-1	C	N	N	C	N	N	N
10.SIN-27 ^c	C	N	N	N	N	N	N
23.ANI-6	N	-	-	-	N	N	N
27.ANI-8	N	N	N	N	N	N	N
28.ANI-9	N	N	N	N	N	N	N
29.ANI-10	C	-	N	+/-	N	N	N
37.ANI-11	C	N	N	C	N	N	N
39.ANI-12	N	N	N	C	N	N	N
93.ANI-21	+/-	N	N	N	N	N	N
103.ANI-24	+/-	-	-	N	N	N	N
111.ANI-27	N	-	-	-	-	-	-

^a: From reference 21

^b: N, Normal induction; -, no induction; C, constitutive; +/-, induction than normal.

^c: SIN, starvation-inducible protein.

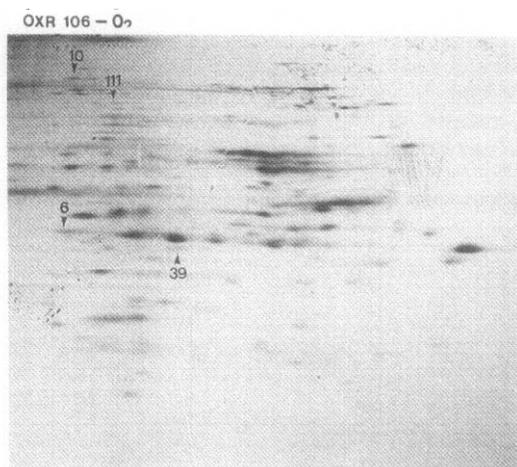


Fig. 5. Two-dimensional patterns of ANI proteins not induced at the anaerobic condition from YK 1037(*ani2013::Mud J oxr106::Tn10*) mutants. Arrowheads designate repressed proteins.

identified loci of other *oxr* mutations.

Because there was *proU* locus, an potential osmoregulatory gene, in the mapping region of the positive regulator *oxr106*, *proU::Tn10* lysate, was transduced to YK132 (parent strain of *oxr106*) and examined its effect to *ani-lacZ* expression. But there was not any *proU* effect to anaerobic expression of *ani-lacZ*. It was shown that these two genes were close each other on the chromosome of *S. typhimurium*.

Two-dimensional electrophoretic analysis of anaerobiosis inducible proteins

The purpose of this procedure was to map the controlling circuitry involved with anaerobic gene expression. YK1011 (*oxr103::Tn10*), one of the negative regulatory mutant, was subjected to two-dimensional electrophoretic analysis of cellular proteins (Fig. 4). The coordinates were used from standard two-dimensional profile of anaerobiosis-inducible proteins as described by Spector *et al.* (21).

Analysis of the *oxr 103* gels showed different patterns to those of known *oxr* mutation (Table 4). The comparison of proteins between *oxr 103* and other known *oxr* mutations were made according to the protein profiles by Spector *et al.* (21). Eleven proteins were regulated by *oxr 103* and eight of them showed the different regulatory pattern compared to those of known *oxr* mutation. It implied that this mutation had two prominent controlling boundary about oxygen regulation. At the other hand, a positive regulator, *oxr106*, repressed several proteins normally induced in anaerobic culture (Fig. 5). ANI-27, ANI-1, ANI-12, and ANI-7 were normally induced by various *oxr* mutation, but analysis of *oxr106* gel showed repressive pattern of these proteins. Although we did not get the aerobic coordinates yet, *oxr106* was thought to a potential regulator ever before.

ACKNOWLEDGEMENT

This research was supported by grant from Ministry of Education, Korea, for the Research Institute of Basic Sciences, Korea University (19 90). We wish to thank Dr. K.E. Sanderson in *Salmonella* Genetic Stock Center for providing us with various *Salmonella* strains.

REFERENCES

1. 김중선, 우영대, 박종희, 김영권, 이인수, 박용근. 1989. *Salmonella typhimurium*에서 Mu dJ(Km, lac) operon fusion을 이용한 산소, 무산소 유도유전자에 관한 연구. 한국미생물학회지. 27: 201-209.
2. Aliabadi, Z., F. Warren, S. Mya and J.W. Foster. 1986. Oxygen-regulated stimulons of *Salmonella typhimurium* identified by Mu d1(Ap lac) operon fusions. *J. Bacteriol.* 165: 780-786.
3. Aliabadi, Z., Y.K. Park, J.L. Slonczewski and J.W. Foster. 1988. Novel regulatory loci controlling oxygen- and pH-regulated gene expression in *Salmonella typhimurium*. *J. Bacteriol.* 170: 842-851.
4. Anne M. Kukral, Kathryn L. Strauch, Russell A. Maurer and Charles G. Miller. 1987. Genetic analysis in *Salmonella typhimurium* with a small collection of randomly spaced insertions of transposon Tn10Δ16Δ17. *J. Bacteriol.* 169: 1787-1793.
5. Bell, A.I., K.L. Gaston. J.A. Cole and S.J.W. Busby. 1989. Cloning of binding sequences for the *Escherichia coli* transcription factors, FNR and CRP; location of bases involved in discrimination between FNR and CRP. *Nucleic Rev.* 17: 3865-3874.
6. Booth, I. 1985. Regulation of cytoplasmic pH in *Bacteria*. *Microbiol Rev.* 49: 359-378.
7. E.A. Auger, K.E. Redding, T. Plumb, L.C. Childs, S.Y. Meng and G.N. Bennett. 1989. Construction of lac fusions to the inducible arginine and lysine decarboxylase genes of *Escherichia coli* K12. *Molecular Microbiology* 3: 609-620.
8. Gottesman, S. 1984. Bacterial regulation: Global regulatory networks. *Ann. Rev. Genet.* 18: 415-441.
9. Haddock, B.A. and C.W. Jones. 1977. Bacterial respiration. *Bacteriol. Rev.* 41: 47-99.
10. Holly, E.A. and J.W. Foster. 1982. Bacteriophage P22 as a vector for Mu mutagenesis in *Salmonella typhimurium*: isolation of nad-lac and pnc-lac gene fusions. *J. Bacteriol.* 152: 959-962.
11. Ingledew, W.J. and R.K. Poole. 1984. The regulatory chains of *Escherichia coli*. *Microbiol. Rev.* 48: 222-271.
12. Jamieson, P.J. and C.F. Higgins. 1986. Two genetically distinct pathways for transcriptional regulation of anaerobic gene expression in *Salmonella typhimurium*. *J. Bacteriol.* 168: 389-397.
13. Jayaraman, P.S., J.A. Cole and S.J.W. Busby. 1989. Mutational analysis of the nucleotide sequence at the Fnr-dependent nirB promoter in *Escherichia coli*. *Nucleic Acids Res.* 17: 135-145.
14. Jones, H.M. and R.P. Gunsalus. 1987. Regulation of *Escherichia coli* fumarate reductase (*frdABCD*) operon expression by regulatory electron acceptors and the *fnr* gene product. *J. Bacteriol.* 169: 3340-3349.
15. Lambden, P.R. and J.R. Geust. 1976. Mutants of *Escherichia coli* K-12 unable to use fumarate as an anaerobic electron acceptor. *J. Gen. Microbiol.* 97: 145-160.
16. Mellman, I., R. Fucho and A. helenius. 1986. Acidification of the endocytic pathways. *Annu. Rev. Biochem.* 55: 663-700.
17. Miller, J.H. 1972. Experiments in molecular genetics. Cold Spring Harbor laboratory, Cold Spring Harbor, N.Y.
18. Nicholas R. Benson and Barry S. Goldman. 1992. Rapid mapping in *Salmonella typhimurium* with Mud-P22 prophages. *J. Bacteriol.* 174: 1673-1681.
19. Shaw, D.J. and J.R. Guest. 1982. Amplification and product identification of the *fnr* gene of *Escherichia coli*. *J. Gen. Microbiol.* 128: 2221-2228.
20. Shaw, D.J., D.W. Rice and J.R. Guest. 1983. Homology between CAP and Fnr, a regulator of anaerobic respiration in *Escherichia coli*. *J. Mol. Biol.* 166: 241-247.
21. Spector, M.P., Z. Aliabadi, T. Gonzalez and J.W. Foster. 1986. Global Control in *Salmonella typhimurium*. Two-dimensional electrophoretic analysis of starvation-, anaerobiosis-, and heat shock-inductive proteins. *J. Bacteriol.* 168: 420-424.
22. Spiro, S., R.E. Roberts. and J.R. Guest. 1989. Fnr-dependent repression of the nah gene of *Escherichia coli* and metal ion requirement for Fnr-regulated gene expression. *Mol. Microbiol.* 3: 601-608.
23. Strauch, K.L., J.B. Lenk, B.L. Gamble and C.G. Miller. 1985. Oxygen regulation in *Salmonella typhimurium*. *J. Bacteriol.* 161: 673-680.
24. Youderian, P., P. Sugiono, K.L. Brewer, N.P. Higgins and T. Elliot. 1988. Packaging specific segments of the *Salmonella chromosome* with locked-in Mud-P22 prophages. *Genetics* 118: 581-592.

(Received July 28, 1992)

(Accepted October 2, 1992)

초 록: *Salmonella typhimurium*에서 무산소 유도 조절유전자의 분리 및 발현

방일수 · 이윤정 · 고상균* · 안정선** · 이영록 · 박용근(고려대학교 생물학과, *대전대학교 미생물학과, **서울대학교 생물학과)

여러개의 *ani-lacZ* 융합 균주들을 pH, 산소, 무산소 변화에 대해 조사하였으며 무산소조건에서 발현이 유도되는 gene의 조절에 관여하는 몇개의 조절유전자를 *Salmonella typhimurium*에서 새롭게 동정, 분석하였다. 또한, 기존의 무산소 유도 *ani-lacZ* 융합균주 중 산성 pH에 의해서도 유도되는 3개의 균주를 확인하였다. 이들은 YK126, YK131, YK132로써, 무산소 조건뿐 아니라 산성 pH조건에서도 높은 β -galactosidase 유도비를 나타내었다. Tn10을 이용해서 분리한 6개의 *oxr* 돌연변이 균주는 두개의 군으로 나누어 진다. 그들 중 5개는 음성적으로 조절하였고 나머지 1개는 양성적으로 조절하였다. 네개의 *oxr*의 유전자좌는 87 min(*oxr101*), 63 min(*oxr104*), 97 min(*oxr105*), 57 min(*oxr106*)으로 54개의 Mud-P22 lysogen에 의해 확인되었다. 2차원 폴리아크릴 아마이드 전기영동(2-D PAGE)을 이용하여 무산소 유도 단백질에 대한 *oxr* 돌연변이의 조절 양상을 확인하였다.