Mutational Analysis of Ligand Recognition by Tcp, the Citrate Chemoreceptor of *Salmonella enterica* Serovar Typhimurium

**TOMONORI IWAMA,† KO-ICHIRO NAKAO, HIROSHI NAKAZATO,‡ SHUZO YAMAGATA,† MICHIO HOMMA,‡ AND IKURO KAWAGISHI**

Department of Biotechnology, Division of Utilization of Biological Resources, Faculty of Agriculture, Gifu University, Gifu 501-1193, and Division of Biological Science, Graduate School of Science, Nagoya University, Chikusa-ku, Nagoya 464-8602, Japan

Received 8 September 1999/ Accepted 8 December 1999

The chemoreceptor Tcp mediates taxis to citrate. To identify citrate-binding residues, we substituted cysteine for seven basic or polar residues that are chosen based on the comparison of Tcp with the well-characterized chemoreceptors. The results suggest that Arg-63, Arg-68, Arg-72, Lys-75, and Tyr-150 (and probably other unidentified residues) are involved in the recognition of citrate.

The closely related enteric bacteria *Escherichia coli* and *Salmonella enterica* serovar Typhimurium have multiple transmembrane receptors that mediate chemotactic responses to amino acids, non-PTS sugars, and other attractants and repellents (2, 11, 25, 26, 34, 35). Some receptors (Tar for aspartate, Tsr for serine, and Trg for ribose and galactose) are found in both species. Others are species specific. Belonging to the Tsr for serine, and Trg for ribose and galactose) are found in both species. Others are species specific. Belonging to the

...
R68C showed no response to citrate up to a concentration of 50 mM. These results suggest that the residues Arg-63, Arg-68, Arg-72, Lys-75, and Tyr-150 are important for sensing citrate.

We next examined the methylation patterns of the mutant receptors by immunoblotting with anti-receptor serum (Fig. 3B) as described previously (32). Tcp is methylated at multiple residues in the cytoplasmic domain, and its methylation level increases and decreases in response to citrate and glycerol, respectively, to result in adaptation (39). Methylation and demethylation of a receptor can be detected as mobility shifts of the protein in sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE): the more the receptor is methylated, the faster it migrates in the gel (3, 4, 9, 10). Tcp-R63C migrated a little faster than wild-type Tcp and the other mutant Tcp receptors. However, the receptor does not seem to be proteolytic fragments but seems to be a full-length receptor: (i) Tcp-R63C expressed in HCB339 appeared as multiple bands corresponding to differential levels of methylation (Fig. 3B), whereas the same receptor expressed in a ΔMCP strain lacking the methyltransferase CheR and the methylesterase/deamidase CheB appeared as a single band with a mobility faster than that of wild-type Tcp (data not shown); (ii) Tcp-R63C was detected with antiserum raised against the C-terminal 20-ami-no-acid sequence of Tar (data not shown), whereas the mutant Tcp receptor lacking the C-terminal residue (Phe-547) was not (H. Okumura, M. Homma, and I. Kawagishi, unpublished results); and (iii) the corresponding mutant (R64C) Tar protein also migrates faster than wild-type Tar (data not shown).

In the absence of citrate, all of the mutant proteins showed methylation patterns similar to that of wild-type Tcp. All of the mutant receptors were demethylated in response to the addition of the repellent glycerol. This result indicates that all of the mutant receptors retain general signaling and adaptation abilities. In the presence of citrate, the receptors which mediated attractant responses to citrate (Tcp-R78C and Tcp-K157C) showed elevated methylation levels. In contrast, citrate did not influence the methylation levels of Tcp-R63C and Tcp-R68C, which failed to mediate responses to citrate and increased only marginally those of Tcp-R72C, Tcp-K75C, and Tcp-Y150C, which mediated weaker responses. These results
indicate that the R63C, R68C, R72C, K75C, and Y150C receptors are fully or partially defective in citrate-stimulated methylation, corresponding well to the defects in behavioral responses to citrate, and that the latter defects are not indirect results from elevated levels of methylation, which would bias the unstimulated behavior toward tumbling. Two SH groups in close vicinity can form a disulfide bond under moderately oxidizing conditions. Indeed, in some Cys-replaced mutants of Tar, the two subunits of the homodimer are cross-linked by a spontaneously formed disulfide bond (27). Thus, the defects in citrate sensing could be due to indirect effects of disulfide cross-linking. We therefore looked for intersubunit disulfide bonds in the Cys-replaced Tcp proteins. After nonreducing SDS-PAGE followed by immunoblotting, bands with apparent molecular masses of about 60 kDa were detected for all samples (Fig. 4A). In addition, with the R68C, K75C, and R78C receptors, we found additional bands with apparent molecular masses of about 130 kDa (Fig. 4A). These bands disappeared by the treatment of the samples with 10% 2-mercaptoethanol prior to SDS-PAGE (Fig. 4A). Therefore, we concluded that these bands represent disulfide-cross-linked homodimers of the mutant Tcp proteins, suggesting that residues 68, 75, and 78 of one subunit of the Tcp homodimer are located near the same residues of the partner subunit. This result corresponds well to a configuration in Tar revealed by a comprehensive survey of disulfide cross-linking in Cys-scanned mutant proteins (7): Ser-68 and Met-75 of the Tar homodimer lie at the interface of helices $\alpha_1$ and $\alpha_1'$. In Tcp, the positional equivalents are Asn-67 and Leu-74, respectively. If Tcp has a similar helical structure, residues 68, 75, and 78 would be located at positions adjacent to the interface, and residue 72 would be in the opposite faces. Moreover, in the case of Tcp-R78C, which had normal sensing abilities, both the cross-linked and the non-cross-linked species showed increases and decreases in the methylation level in response to citrate and glycerol, respectively (Fig. 4B). Even in the case of R68C and K75C, which were defective in citrate sensing, the methylation levels of the cross-linked dimers decreased in response to glycerol (Fig. 4B). This finding suggests that Tcp forms a functional homodimer regardless of ligand occupancy states, as demonstrated for Tar (7, 8, 12, 24, 29), Tsr (23), and Trg (1, 16, 20). For R68C, K75C, and R78C, the fractions of the cross-linked dimers were 0.2, 0.6, and 0.5, respectively. Thus, substantial amounts of uncross-linked homodimers are always available, even for mutant receptors that undergo cross-linking. Moreover, the addition of dithiothreitol (up to 50 mM) did not improve citrate responses of HCB339 cells expressing any of these receptors (data not shown). Therefore, it is likely that loss of the positively charged side chains of Arg-68 and Lys-75 itself impairs the ligand-binding affinity of Tcp for citrate. Taken together, the data suggest that the residues Arg-63,
Arg-68, Arg-72, Lys-75, and Tyr-150 are involved in the recognition of citrate.

Tar has two rotationally symmetrical, antiparallel, nonoverlapping ligand-binding sites at the subunit interface (28, 40). Arg-64 in one subunit of the Tar homodimer interacts with the α-carboxyl group of aspartate, and Tyr-149 in the same subunit interacts with the α- and β-carboxyl groups via water molecules. Arg-69 and Arg-73 in the other subunit interact with the β-carboxyl group of aspartate. Presumably, some of the three carboxyl groups or the hydroxyl group of citrate may interact with Arg-68 and Arg-72 in one subunit of the Tcp homodimer and with Arg-63 and Tyr-150 in the other subunit. Lys-75 may also interact with some of the carboxyl groups and/or the hydroxyl group of citrate and may be one of the residues responsible for the ligand specificity, because this lysine is not conserved in Tar or Tsr. In contrast, the closely located basic residue Arg-78 does not seem to be involved in ligand recognition. Another candidate for a determinant of ligand specificity is Lys-157. In Tar, the amino group of aspartate interacts with Thr-154, which is not conserved in Tcp. Instead, Tcp has the basic residue Lys-157 in this region. However, the substitution of Cys for Lys-157 did not affect citrate sensing at all.

Binding of aspartate to Tar does not cause a large rearrangement between TM1–α1 and TM1′–α1′ (5, 6, 7, 16, 20, 27) or between TM1–α1 and α4′–TM2′ (36) but triggers a slight axial movement of α4–TM2 relative to TM1–α1 and TM1′–α1′ (6, 16, 33). It is this movement that transmits information about the extracellular binding event to the cytoplasmic signaling domain. Based on the homology of Tcp with Tar, it is assumed that residues 63, 68, 72, and 75 of Tcp are located at the apex of α1 and that residue 150 is near the apex of α4. Tcp would seem to transduce signals via a similar process. However, our results also imply a possible difference between Tcp and Tar. The critical movement of α4 in Tar presumably involves Thr-154 (Thr-156 in Tsr), since it is a major contact with the ligand in α4. Lys-157 would play a similar role in Tcp, but unexpectedly the K157C mutant was normal for citrate taxis.

In this study, we targeted several residues in the putative ligand-binding regions for Cys replacement. The mutants can be further characterized by chemical modification as has been successfully applied to Tar (14, 15) and Tsr (17, 18). These polar and positively charged residues were chosen for mutagenesis, based on the homology of Tcp with the well-characterized chemoreceptors Tar and Tsr. Among the residues at which Cys substitutions disrupted citrate taxis, Arg-63, 68 and 72 are conserved in Tar and Tsr and Tyr-150 is conserved in Tar. Lys-75 is the only residue unique to Tcp. It is likely that some other residues also interact with citrate. Further experiments, such as random mutagenesis, are needed to elucidate the precise molecular mechanism underlying the recognition of citrate, including discrimination between citrate and a metal ion-citrate complex.

We thank Michael D. Manson of Texas A & M University for critically reading the manuscript.

This work was supported in part by grants-in-aid for scientific research to I.K. from the Ministry of Education, Science, Sports and Culture of Japan and from the Takeda Science Foundation.

REFERENCES

FIG. 4. Detection of disulfide-cross-linked dimers of the mutant Tcp proteins in nonreducing SDS-PAGE followed by immunoblotting. (A) Detection of cross-linked dimers of Tcp. Ice-cold 5% trichloroacetic acid was added to HCB339 (ΔMCP) cells expressing wild-type (WT) or mutant Tcp proteins pretreated with or without 10 mM N-ethylmaleimide (NEM). NEM was added to prevent disulfide formation during sample preparation. The NEM-pretreated or untreated samples were collected by centrifugation and were dissolved in nonreducing SDS loading buffer supplemented with 10 mM NEM (lanes labeled with NEM) or 10% 2-mercaptoethanol (lanes labeled with 2ME), respectively. These samples were subjected to nonreducing SDS-PAGE followed by immunoblotting. (B) Methylation patterns of cross-linked and uncross-linked Tcp proteins. HCB339 (ΔMCP) cells expressing wild-type or mutant Tcp were incubated with 15% glycerol (Glyc), distilled water (None), 10 mM citrate (Cit-10), or 50 mM citrate (Cit-50) at 25°C for 30 min. After stimulation, the samples were treated with 10 mM NEM and 5% trichloroacetic acid and were further treated as described above.