

Association of *pharaonis* phoborhodopsin with its cognate transducer decreases the photo-dependent reactivity by water-soluble reagents of azide and hydroxylamine

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Abstract

pharaonis phoborhodopsin (ppR; also *pharaonis* sensory rhodopsin II, psRII) is a receptor of the negative phototaxis of *Natronobacterium pharaonis*. In halobacterial membrane, ppR forms a complex with its transducer pHtrII, and this complex transmits the light signal to the sensory system in the cytoplasm. In the present work, the truncated transducer, t-Htr, was used which interacts with ppR [Sudo et al. (2001) Photochem. Photobiol. 74, 489–494]. Two water-soluble reagents, hydroxylamine and azide, reacted both with the transducer-free ppR and with the complex ppR/t-Htr (the complex between ppR and its truncated transducer). In the dark, the bleaching rates caused by hydroxylamine were not significantly changed between transducer-free ppR and ppR/t-Htr, or that of the free ppR was a little slower. Illumination accelerated the bleach rates, which is consistent with our previous conclusion that the reaction occurs selectively at the M-intermediate, but the rate of the complex was about 7.4-fold slower than that of the transducer-free ppR. Azide accelerated the M-decay, and its reaction rate of ppR/t-Htr was about 4.6-fold slower than free ppR. These findings suggest that the transducer binding decreases the water accessibility around the chromophore at the M-intermediate. Its implication is discussed. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Bleach of retinoid protein; Flash photolysis; Sensory rhodopsin; *Halobacterium salinarum*; *Natronobacterium pharaonis*

1. Introduction

The archaeon *Halobacterium salinarum* has four retinal proteins (archaeal rhodopsins), which are bacteriorhodopsin (bR) [1,2], halorhodopsin (hR) [3–5], sensory rhodopsin (sR, also called sRI) [6–8] and

phoborhodopsin (pR, also called sRII) [9–11]. The former two, bR and hR, are light-driven ion pumps for proton and chloride, respectively. The latter two, sR and pR, are photoreceptors of this archaeon [9,11]. The ground state of sR (or sRI, the absorption maximum λ_{\max} of 587 nm) is a receptor mediating positive phototaxis, whereas its long-lived photo-intermediate (S373, λ_{\max} of 373 nm) acts as a receptor of negative phototaxis. pR (or sRII) absorbs maximally 487 nm light and works as a receptor of negative phototaxis [9]. Each receptor transmits its signals through integral membrane transducer proteins HtrI and HtrII [12–15] that are considered to

Abbreviations: DM, *n*-dodecyl- β -D-maltoside; pHtrII, *pharaonis* halobacterial transducer of ppR; ppR, *pharaonis* phoborhodopsin (*pharaonis* sensory rhodopsin II); t-Htr, truncated pHtrII; MRT, mean residence time; ppR_M, M-intermediate of ppR

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form a signaling complex firmly with respective receptors. The Htr proteins both have a signaling domain and two methylatable domains [11,16,17] such as an aspartate receptor (Tar) in *Escherichia coli* [18], and their proteins activate a phosphotransfer cascade producing flagella motor responses. By these signaling systems, these bacterial cells move toward a longer wavelength light ($\lambda > 520$ nm) where bR and hR work, while they avoid a shorter wavelength light ($\lambda < 520$ nm) which contains harmful near-UV light.

It is reported that *Natronobacterium pharaonis* also has pR (sRII)-like proteins [19–22]. The protein is called *pharaonis* pR (abbreviated as ppR; or *pharaonis* sRII, psRII). ppR transmits its signal through transducer protein pHtrII, the same as sR and pR. Recently, we [23] and Wegener et al. [24] succeeded in an expression of a truncated pHtrII (named as t-Htr) in *E. coli*, where t-Htr is an N-terminal sequence of 159 amino acid residues of pHtrII. This t-Htr has the ability of exact contact with ppR, meaning that ppR/t-Htr (complex between ppR and t-Htr) serves as an adequate model system to elucidate the signal transfer. We [23] previously reported that the stoichiometry of ppR/t-Htr complex is 1:1. The functional unit of HtrI is considered to be a dimer [25]. If we accept this, the stoichiometry of ppR and pHtrII would be 2:2.

pHtrII-free ppR can transport protons on illumination [26,27]. On the other hand, this does not occur in the ppR/pHtrII complex [26,27] although the proton circulation (proton uptake and release occurs on the same side) is observed. We interpreted this as follows: at M-intermediate the cytoplasmic channel (CP) of ppR may be closed by the association with pHtrII, whose idea was first proposed by Spudich et al. [8] on the basis of HtrI blockage of proton flux through the CP channel of sRI [28]. In the present paper, we attempt to obtain the evidence for the difference in conformational changes around the chromophore between transducer-free ppR and ppR/t-Htr.

Azide and hydroxylamine can react with the transducer-free ppR: (1) azide accelerates greatly the decay of the M-intermediate (ppR_M), the re-protonation process of Schiff base that forms between the chromophore and the ϵ -amino group of a lysine residue [29] and (2) hydroxylamine attacks the Schiff

base mainly at ppR_M state to bleach the pigment [30,31]. Since these two reagents are water-soluble, the increase in their reactivity is considered to be caused mainly by the increase in the accessibility of these reagents to the hydrophobic moiety of the protein. Therefore, the reactivity of these reagents is a good indicator for the environmental change around the Schiff base. The present paper shows the decrease in the reactivity of both water-soluble reagents when the ppR/t-Htr complex forms, which supports the concept of transducer-closure of the CP channel.

2. Materials and methods

2.1. Sample preparations

The expression of histidine-tagged recombinant ppR and t-Htr in *E. coli* BL21 (DE3), preparation of crude membranes and its purification were described previously [32,33]. The complex of ppR/t-Htr was prepared as previously described [23]. Sample media were exchanged by ultrafiltration (UK-50, Advantech, Tokyo, Japan) and finally samples were suspended in a buffer solution containing 400 mM NaCl, 10 mM Tris-HCl (pH 7.0) and 0.1% DM (*n*-dodecyl- β -D-maltoside).

2.2. Reaction with hydroxylamine

Sample proteins were suspended in the buffer solution described above supplemented with 50 mM hydroxylamine. For the transducer-free ppR, the concentration of 5 μ M was used. The complex of ppR/t-Htr was prepared by mixing 5 μ M (final concentration) of ppR and 50 μ M (final concentration) of t-Htr. The presence of 10-fold excess t-Htr was required for the complete complex formation of ppR, details of which were described previously [23]. When necessary, samples were irradiated with a green light (with an interference filter of 506 nm, KL-50, Toshiba, Tokyo, Japan). A hot-mirror was placed in front of the projector lamp (halogen-tungsten, 1 kW) to remove the heat radiation. The bleach process was monitored either by a spectrophotometer (V-560, Jasco, Tokyo, Japan) or by flash photolysis (see below). Experiments were done at 20°C.

2.3. Reaction with hydroxylamine under pulse illumination

Preparation of the protein samples and the suspension medium were the same as those of the steady illumination. Pulse illumination was provided every 25 s with a Xe-flash lamp (duration of 250 μ s) through an interference filter (KL-54, Toshiba, Tokyo, Japan) and a cut-off filter (Y52, Hoya, Tokyo, Japan). The bleaching was monitored by the absorbance at 500 nm.

2.4. Flash photolysis spectroscopy and calculation of the mean residence time (MRT)

Apparatus and procedure of the flash photolysis were essentially the same as described previously [34]. The M-decay was monitored at 350 nm. The MRT of ppR_M was defined previously [30].

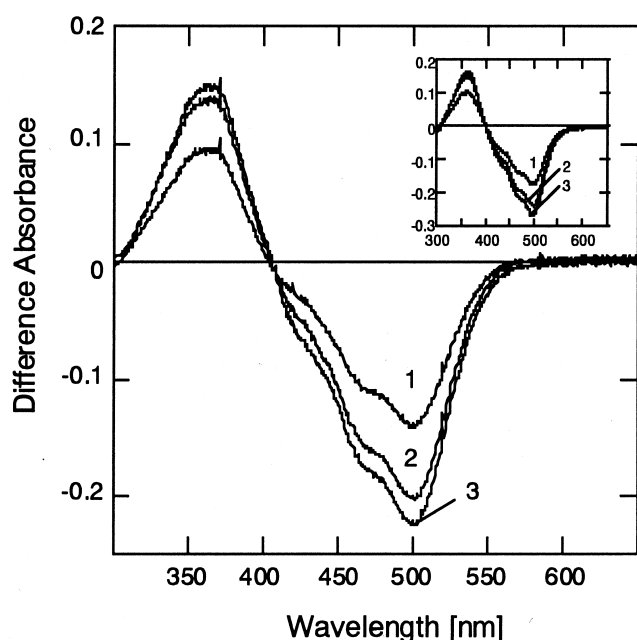


Fig. 1. Photo-induced difference spectra of the $ppR/t-Htr$ complex and the transducer-free ppR (inset). Each spectrum (curves 1–3) was recorded at 2, 5 and 20 min after the addition of hydroxylamine, respectively. Illumination was provided with green light (506 nm at the intensity of 35 W/m^2). Proteins were suspended in 400 mM NaCl, 50 mM hydroxylamine, 0.1% DM and 10 mM Tris-HCl of which the pH was adjusted at pH 7.0. Temperature was kept constant at 20°C. Protein concentrations were 5 μ M for the transducer-free ppR , and the complex of $ppR/t-Htr$ was formed by adding 5 μ M of ppR and 50 μ M of $t-Htr$.

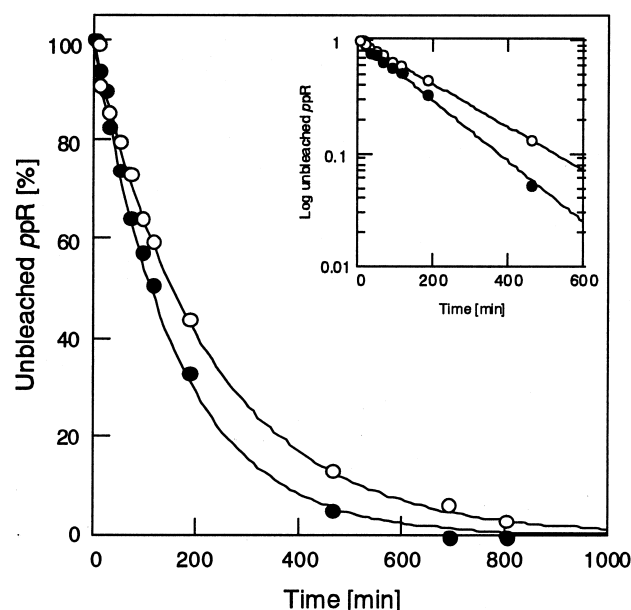


Fig. 2. Reactivity of ppR to hydroxylamine in the presence and absence of $t-Htr$ in the dark. Experimental conditions such as solution compositions, protein concentrations, hydroxylamine concentration and temperature were the same as those in Fig. 1. The unbleached amounts of ppR were estimated by flash photolysis. Open circles represent data of the transducer-free ppR and closed circles those of the $ppR/t-Htr$ complex. Inset shows the logarithmic plot.

3. Results

Fig. 1 shows the absorption spectra of $ppR/t-Htr$ complex at varying times after the constant illumination, and inset shows that obtained with the transducer-free ppR . The decreases in the absorbance at 500 nm and the concomitant increases in the absorbance at 360 nm were observed. The changes in these are proportional to each other with an isosbestic point of 400 nm, implying that hydroxylamine can attack the Schiff base of the $ppR/t-Htr$ complex, as is similar to the transducer-free ppR (see inset).

The bleach by hydroxylamine in the dark was next examined. The amounts of unbleached protein were estimated by amplitudes of the flash-induced absorbance change. The ordinate of Fig. 2 represents the ratio of flash-induced absorbance changes after the incubation in the dark to that before the incubation. Open circles are the data of the transducer-free ppR and closed circles are those of the complex. The inset shows the semi-logarithmic plot, meaning that the reactions follow first order kinetics. The bleaching

rate of the transducer-free *ppR* was calculated to be 0.0044 min^{-1} , and that of the *ppR/t-Htr* was 0.0062 min^{-1} . Note that in the dark the rate of the transducer-free *ppR* is 1.4-fold slower than that of the complex.

Comparison of data shown in Figs. 1 and 2 shows that the illumination accelerates greatly the bleaching rate, implying that photo-intermediate(s) has much higher reactivity than the ground state. In fact, we showed that hydroxylamine reacted selectively with *ppR_M* of the transducer-free *ppR* [30]. Since a photo-intermediate is attacked during the photocycling whose decay rates are different between the transducer-free *ppR* and the complex, the actual period for the reaction of hydroxylamine with an intermediate differs between the samples if the experimental condition of the steady illumination is employed. We, then, employed the pulse illumination as was used previously [30]. Results obtained are shown in Fig. 3, where the normalized amounts of unbleached *ppR* in the logarithmic scale are plotted against the number of flashes provided. This figure reveals the lower bleaching rate of the *ppR/t-Htr* complex

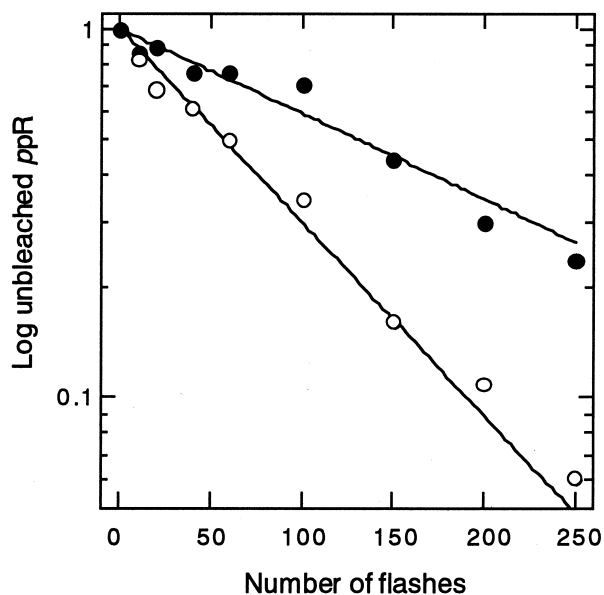


Fig. 3. Flash-induced bleach by hydroxylamine for the transducer-free *ppR* (open circles) and for the *ppR/t-Htr* complex (closed circles). The ordinate represents the normalized amounts of unbleached (alive) pigment estimated by the amplitude of flash photolysis (at 500 nm) in the logarithmic scale, and the abscissa the number of flashes. The experimental conditions were the same as in Fig. 1.

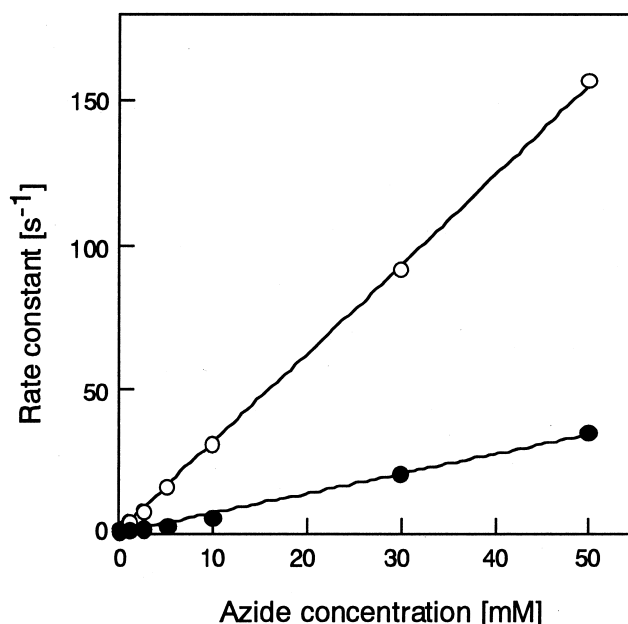


Fig. 4. Azide accelerates the *ppR_M* decay, but the effects differ between the transducer-free *ppR* (open circles) and the *ppR/t-Htr* complex (closed circles). Samples were suspended in a buffer solution containing 400 mM NaCl, 10 mM Tris-HCl (pH 7.0) and 0.1% DM which was added by varying concentrations of azide. Temperature was 20°C. The slopes are: $3.1 \text{ s}^{-1} \text{ mM}^{-1}$ for the transducer-free *ppR* (open circles) and $0.68 \text{ s}^{-1} \text{ mM}^{-1}$ for the *ppR/t-Htr* complex (closed circles).

(closed circles) than the transducer-free *ppR* (open circles). Although one flash evokes one chance of the reaction to the intermediate (*ppR_M*, see later), the lifetimes of *ppR_M* are different and this correction must be necessary. Under the present condition, the M-decay time constants are 1.56 s^{-1} for the transducer-free *ppR*, and 0.90 s^{-1} for the *ppR/t-Htr* complex. It is noted that if the decay follows the single exponential equation, the mean lifetime of the intermediate or MRT (see later) is equal to the reciprocal of the decay constant. This correction led to a 7.5-fold decrease of *ppR*s by the association with its transducer.

Azide accelerates the decay of *ppR_M* [29]. We measured *ppR_M* decay rates of both the transducer-free *ppR* and *ppR/t-Htr* complex in the presence of varying concentrations of azide. The decay rate constants were calculated by a single exponential equation as was previously employed [23]. Results are shown in Fig. 4. Both rate constants increased with an increase in the azide concentration. Under the azide concentration range examined, the rate increased linearly;

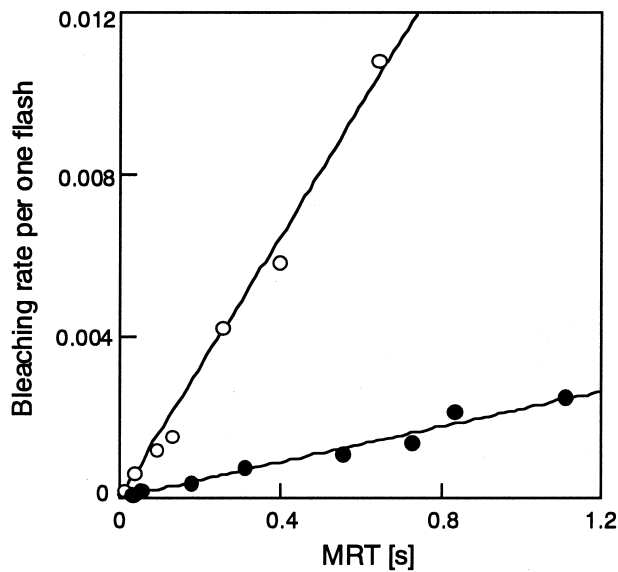


Fig. 5. Bleaching rates per one flash are plotted against the MRT of the M-intermediate. Open circles represent data of the transducer-free *ppR* and closed circles are those of the *ppR*/t-Htr complex. The calculation of MRT should be referred in [29]. The values of MRT were changed by adding various concentrations of azide. Bleaching rates per one flash were calculated from the slope of the plots similar to Fig. 3, and were corrected by subtracting the bleaching rate in the dark. It is noted that the bleaching rate in the dark could not be neglected because more than 100 min was required to achieve the measurement for each azide concentration. Experimental conditions were the same as in Fig. 1 except for azide concentration.

when azide concentration is much larger than this range, the increase in the rate may level off as in [29]. The slope for the transducer-free *ppR* is 4.6-fold larger than that for the complex.

Previously we [30] showed that hydroxylamine reacts with M-intermediate of the transducer-free *ppR*. The experiments were done in the presence of varying concentrations of azide that accelerates the M-decay in a concentration-dependent manner but does not affect the L-decay (M-formation) neither the O-decay. Addition of azide, hence, modifies only the lifetime of *ppR_M*. The most convincing result was the strict proportional relationship between the bleaching rate and the MRT of *ppR_M*. Similarly, the rate of M-formation using the *ppR*/t-Htr complex was not changed (data not shown). We examined the relationship between the bleaching rate and MRT of M-intermediate under varying concentrations of azide. Results are shown in Fig. 5, revealing

that *ppR_M* of the *ppR*/t-Htr complex reacts with hydroxylamine, the same as the transducer-free *ppR*. In this figure, data of the transducer-free *ppR* were also plotted. The *ppR*/t-Htr complex obviously shows the high resistance against the hydroxylamine. The slope in the absence of t-Htr is 7.4-fold larger than that in the presence of t-Htr.

4. Discussion

As shown in Fig. 2, hydroxylamine was able to attack the Schiff base of both the transducer-free *ppR* and the *ppR*/t-Htr complex in the dark, but their rates were very small. The bleach rate of the complex was a little faster (1.4-fold) than that of the free *ppR*. The amounts of unbleached pigments were estimated by the amplitude of flash photolysis. Illumination accelerated the bleach and the complex was more resistant against hydroxylamine under illumination than free *ppR* (see Fig. 3). Then, the difference of the bleach rate between the free form and the complex might be a little larger than the 1.4-fold difference. This difference, on the other hand, means the complex formation of *ppR*/t-Htr in the dark.

In the dark, sR (or sRI) chromophore exhibits stability to hydroxylamine bleaching in the presence of HtrI. Removal of HtrI accelerates the bleaching rate by 2.4-fold [35]. On the other hand, for *ppR*, the presence of t-Htr increased the bleaching rate in the dark although the effect of t-Htr was small. The reason for the opposite tendency observed between *ppR* (*psRII*) and sR (sRI) is not known at present, but maybe comes from a structural difference in the ground state between sR/HtrI and *ppR*/t-Htr complex.

Illumination accelerates greatly the bleaching by hydroxylamine. Previously we [30] showed the *ppR_M* selectively attacked by hydroxylamine using the transducer-free *ppR*. This paper shows that for the *ppR*/t-Htr complex, *ppR_M* is also a selective target attacked by hydroxylamine (Fig. 5). We applied the pulse illumination instead of the steady illumination in order to avoid the complexity originated from the difference in the photocycling rate. After the correction of the lifetimes of *ppR_M* of the transducer-free and associated *ppR*, we reached the conclusion that the association with the transducer decreases the

reactivity of hydroxylamine by about 7.5-fold (Fig. 3). Results shown in Fig. 5 gave the same conclusion.

Subramaniam et al. [36] showed the L-intermediate of bR as the species that is reactive to hydroxylamine and this intermediate has protonated Schiff base. On the other hand, for *ppR*, M-intermediate is the species that has deprotonated Schiff base. In the dark, sR (sRI) chromophore is much easier to be bleached than bR [35], and their Schiff bases are both protonated. Although the rates were very small, the rate of the wild-type *ppR* in the dark is one order larger than that of D75N under illumination [30]; both Schiff bases are protonated. These facts suggest that the reactivity of the Schiff base with hydroxylamine is influenced by the local environment of the chromophore. Because hydroxylamine is water-soluble, the susceptibility of this reagent might be reflected by the water accessibility around the chromophore. Therefore, we may conclude that association with the transducer reduces the water accessibility around the chromophore at *ppR_M* state.

Recent reports on the structure of bR and its mutants [37–41] reveal the movement of helices during the photocycle. The conformational change is largely located at the cytoplasmic end of helices F and G. These movements open a narrow water-accessible channel in the protein, enabling the transfer of a proton from an aspartate residue to the Schiff base. Similar helix movements during photocycle were also suggested in *ppR* by electron paramagnetic resonance spectroscopy [24]. Under the condition that the transducer is present near *ppR*, the mobility of the spin label located at the side-chain of *ppR* decreases slightly. In other words, the photo-induced movement of helix F (or G) may be hampered by t-Htr.

Proton uptake occurred at the *ppR_M* decay and the electrogenic proton transport from the cytoplasmic to the extracellular space was observed for the transducer-free *ppR* [26,27]. This is interpreted as: at *ppR_M* or at its decay the CP channel may open, leading to an increase in water accessibility to Schiff bases, which results in increase in the reactivity. When *ppR* associates with the transducer, the electrogenic proton transport (but in *ppR* transport is far less than in bR [27]) stops and only proton circulation (uptake and release presumably at the extracellular channel) occurs [26]. This observation can be interpreted by the model of Spudich et al. [8] which

is based on the helix tilt described above; the association of sRI or sRII (pR) with their respective transducer closes the CP channel, and the signal transmission is done by membrane helix–helix interaction that is induced by the movement of the helices of the pigment. This closing of the CP channel may reduce the reactivity of hydroxylamine.

The mechanism of the azide effect on M-decay is proposed based on two thoughts. One is that azide binds near D85 of bR (D75 of *ppR*) to create hydrogen networks in the CP channel [42], and the other is a shuttle mechanism through the CP channel, details of which are described in [29,43]. When we adopt the shuttle mechanism, the association with the transducer makes the CP channel narrow, thus resulting in decrease in the azide effect. Although the former is observed in bR and although no experimental data are available showing the validity for *ppR*, this mechanism leads to the conformational change in CP channel by association of t-Htr, which may also be accountable for the experimental findings. We could not rule out the possibility that amounts of the bound azide around D75 are larger for the transducer-free *ppR*.

In the present paper, we showed that association of *ppR* with the transducer reduces the reactivity of *ppR_M* to two water-soluble reagents of hydroxylamine and azide. These observations are consistent with the model that the transducer hampers the photo-induced outward helix movement of the pigment, which leads to the decrease in the reactivity with water-soluble reagents. This is consistent with the signal transduction mechanism proposed by Spudich [8,14].

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