J. Biochem. **127**, 151–161 (2000)

Expression of Functional M_2 Muscarinic Acetylcholine Receptor in *Escherichia coli*[1]

Hiroyasu Furukawa[2] and Tatsuya Haga

Department of Neurochemistry, Faculty of Medicine, The University of Tokyo, 7–3–1 Hongo, Bunkyo-ku, Tokyo 113–0033

Received August 26, 1999; accepted October 26, 1999

The M_2 muscarinic acetylcholine receptor mutant (M_2 mutant), with a lack of glycosylation sites, a deletion in the central part of the third inner loop, and the addition of a six histidine tag at the C-terminus, was fused to maltose binding protein (MBP) at its N-terminus and expressed in *Escherichia coli*. The expression level was 0.2 nmol receptor per 100 ml culture, as assessed as [^{3}H]L-quinuclidinyl benzilate ([^{3}H]QNB) binding activity, when the BL 21 strain was cultured at 37°C to a late growth phase and the expression was induced by isopropyl β-thiogalactoside at 20°C. No [^{3}H]QNB binding activity was detected when it was not fused to MBP or when expression was induced at 37°C instead of 20°C. The MBP-M_2 mutant expressed in *E. coli* showed the same ligand binding activity as the M_2 mutant expressed in the *Sporodoptera frugiperda* (Sf9)/baculovirus system, as assessed as displacement of [^{3}H]QNB with carbamylcholine and atropine. The MBP-M_2 mutant was solubilized, purified with Co^{2+}-immobilized Chelating Sepharose gel and SP-Sepharose, and then reconstituted into lipid vesicles with G protein G_o or G_{i1} in the presence or absence of cholesterol. The reconstituted vesicles showed GTP-sensitive high affinity binding for carbamylcholine and carbamylcholine-stimulated [^{35}S]GTPγS binding activity in the presence of GDP. The proportion of high affinity sites for carbamylcholine and the extent of carbamylcholine-stimulated [^{35}S]GTPγS binding were the same as those observed for the M_2 mutant expressed in Sf9 cells and were not affected by the presence or absence of cholesterol. These results indicate that the MBP-M_2 mutant expressed in *E. coli* has the same ability to interact with and activate G proteins as the M_2 mutant expressed in Sf9, and that cholesterol is not essential for the function of the M_2 muscarinic receptor.

Key words: cholesterol, *Escherichia coli*, G protein–coupled receptor, muscarinic acetylcholine receptor, reconstitution.

G protein–coupled receptors (GPCRs) are known to be involved in diverse functions (*1*, *2*). The ligands for GPCRs include transmitters, hormones, pheromones, and odors. Upon ligand binding, GPCRs activate heterotrimeric G proteins by catalyzing GDP–GTP exchange on their α subunits (Gα), thereby causing dissociation of the α and βγ subunits (Gβγ). Gα and Gβγ activate or inhibit enzymes that give rise to the formation or breakdown of the second messengers in cells and regulate ion channels in cell membranes. The muscarinic acetylcholine receptor belongs to this superfamily of GPCRs. There are five subtypes of muscarinic receptors (*3*, *4*): the M_1, M_3, and M_5 subtypes couple to G_q/G_{11} type G proteins, and the M_2 and M_4 subtypes couple to G_i/G_o type G proteins. Muscarinic receptors are broadly expressed from peripheral tissues such as salivary glands (M_1 and M_3), sweat glands (M_3), ileum (M_2, M_3), and heart (M_2), to the central nervous system (M_1–M_5).

The expression levels of GPCRs are usually less than 1 pmol/mg protein. The development of a high expression system is essential for molecular characterization of GPCRs including muscarinic receptors, particularly for structural studies involving electron or X ray crystallography. The system involving baculovirus and insect cultured cells like Sf9 has been successfully used for large scale expression of GPCRs (*5–8*). Muscarinic receptors have been expressed in this system, and have been shown to have the same ligand binding and G protein activating activity as those extracted from mammalian tissues or expressed in mammalian cultured cells (*5*, *9*, *10*). However, considering the time and cost required for culturing Sf9 cells, a more easily handled expression system is desirable. Muscarinic receptors have also been expressed in *Saccharomyces cerevisiae* (*11*) and BY 2 tobacco cells (*12*), although the expres-

[1] This work was supported in part by grants from the Japan Society and Technology Corporation (CREST), and the Japan Society for the Promotion of Science (Research for Future Program).

[2] To whom correspondence should be addressed: Phone: +81-3-5841-3560, Fax: +81-3-3814-8154, E-mail: furukawa@m.u-tokyo.ac.jp

Abbreviations: M_2, M_2 muscarinic acetylcholine receptor; G protein, guanine nucleotide–binding regulatory protein; GPCR, G protein–coupled receptor; MBP, maltose binding protein; *E. coli*, *Escherichia coli*; Sf9, *Sporodoptera frugiperda*; 5-HT, 5-hydroxytryptamine (serotonin); IPTG, isopropyl-β-D-thiogalactopyranoside; [^{3}H]QNB, [^{3}H]L-quinuclidinyl benzilate; [^{3}H]NMS, [^{3}H]*N*-methylscopolamine; GTPγS, guanosine 5'(3-*O*-thio)triphosphate; CHAPS, 3-[(3-cholamidopropyl)dimethylammonio]-1-propanesulfonic acid; DTT, dithiothreitol; GST, glutathione S-transferase; Trx, thioredoxin.

© 2000 by the Japanese Biochemical Society

Downloaded from http://jb.oxfordjournals.org/ at Cold Spring Harbor Laboratory on March 7, 2012

sion levels in both systems were low: 20 fmol/mg protein for *S. cerevisiae* and 2.0–2.5 pmol/mg protein for BY 2 tobacco cells. Because of its ease in culturing, *E. coli* is considered to be one of the most efficient expression systems for acquiring proteins of interest. There have been several reports on the expression of GPCRs in *E. coli* (*13*). The β_2-adrenergic receptor was first expressed among GPCRs and was found to retain ligand binding activity (*14*). The $5HT_{1A}$ receptor expressed in *E. coli* was reported to interact with G proteins (*15*). However, the expression levels in these studies were low. Grisshammer *et al.* have shown that a relatively high amount of neurotensin receptor can be expressed in *E. coli* through the fusion of MBP at the N-terminus of the receptor (15 pmol/mg protein) (*16*, *17*). The M_1 muscarinic receptor (*18*) and dopamine D_2 receptor (Ito and Haga, unpublished data) have also been expressed successfully using the same strategy as for the neurotensin receptor. These receptors have been shown to have the same ligand binding activity as mammalian receptors, but it remains unknown if they have the same ability to interact with G proteins. In the present study, we have expressed the M_2 muscarinic receptor as a MBP fusion protein in *E. coli* using the strategy used for the expression of neurotensin receptors (*16*, *17*). The expressed receptor, which was purified and reconstituted into lipid vesicles, was found to have the same ligand binding and G protein activating activities as the M_2 muscarinic receptor expressed in Sf9 cells.

We have also examined if cholesterol is necessary for the function of muscarinic receptors. Cholesterol, either by changing the physical properties of biological membranes or by directly interacting with proteins, can modulate the function of membrane proteins (*19*). A well known example is the nicotinic acetylcholine receptor, which loses its cation channel function in the absence of cholesterol (*20*, *21*). There have been several reports on the role of cholesterol in the function of GPCRs: for some receptors including β-adrenergic (*22*), muscarinic (*23*), and oxytosin receptors (*24–26*), cholesterol has been reported to be required for retention of ligand binding activity or for increasing the affinity of receptors for ligands, and for other receptors including dopamine D_1 receptor (*27*) and rhodopsin (*28*), cholesterol has been reported to inhibit their activation. These results were obtained through experiments involving membrane preparations or proteoliposomes in which detergent-solubilized proteins were reconstituted, and these preparations may contain various levels of cholesterol. Definite answers regarding the requirement of cholesterol should be obtained through experiments involving the reconstitution of purified and cholesterol-free GPCRs and G proteins in a defined composition of lipids. We took advantage of the fact that the membrane of *E. coli* does not contain any cholesterol (*29*). Here, we provide evidence that the muscarinic receptor can activate G proteins in the absence of cholesterol.

MATERIALS AND METHODS

Materials—PET25b(+), BL 21, and BL21(DE3) were purchased from Novagen; pGEX-2T, Chelating Sepharose fast flow, SP-Sepharose, and Sephadex G50 from Pharmacia; GTP, GTPγS, GDP, PC, PI, cholesteryl hemisuccinate, CHAPS, and digitonin from Sigma; sodium cholate from WAKO; [^{3}H]NMS, [^{3}H]QNB, and [^{35}S]GTPγS from NEN Dupont; His-probe and Goat anti rabbit IgG (horseradish peroxidase) from Santa Cruz; PVDF membranes from Millipore; and GF/B glass fiber filters from Whatman. The pRG/II-MBP and pT-Trx vectors were kind gifts from Dr. Grisshammer (MRC Center, Cambridge, UK) and Dr. Ishii (RIKEN, Tsukuba), respectively.

Strains, Expression Vectors, and Culture Conditions—The expression vector pRG/II-MBP was used in the present experiment. This expression vector contained most of MBP under the control of the lac promoter and the double ribosomal binding site of the vector pASK40 (*17*). We used the M_2 muscarinic receptor mutant (M_2 mutant), M_2(N-D)-(6His)(I3del) (*10*), in which most of the third internal loop (233–380) was deleted, a six histidine tag (6xHis) and a thrombin cleavage site were added to the C-terminus, and Asn 2, 3, 6, and 9 were replaced by Asp to prevent *N*-glycosylation (Fig. 1a) (*10*). Various expression vectors were constructed to express the M_2 mutant (Fig. 1b).

The M_2 mutant starting from Asp 2 was fused to MBP at its N-terminus between the *Bam*HI and *Pst*I sites of the pRG/II-MBP vector (pRGII/MBP-M_2 mutant). The same coding sequence as that of the pRGII/MBP-M_2 mutant was inserted down stream of the T7 promoter and a ribosomal binding site of PET25b(+) between the *Nco*I and *Hin*dIII sites. The resultant vector, the PET25(+)-MBP-M_2 mutant, contained a pel B signal sequence (*30*) at its N-terminus. The PET25(+)-MBP-M_2 mutant was digested with *Nde*I and *Nco*I, followed by blunt ending and ligation to remove sequences that encode pel B to construct the PET25(–)-MBP-M_2 mutant. The PET25(+)-M_2 mutant was constructed by inserting the whole sequence of the M_2 mutant between the *Nco*I and *Hin*dIII sites of PET25b(+). The thioredoxin (Trx) sequence derived from *E. coli* strain K12 was isolated from the vector pT-Trx, which includes Trx under the control of the T7 promoter (*31*), by PCR. The resultant Trx gene was inserted into the C-terminus of the MBP-M_2 mutant between the *Not*I and *Hin*dIII sites [pRGII/MBP-M_2 mutant-Trx(+His)]. The pRGII/MBP-M_2 mutant-Trx(-His) did not include 6xHis between the M_2 mutant and Trx. GST was also inserted into the N-terminus of the M_2 mutant. The pGEX-2T vector was digested with *Bam*HI and *Eco*RI, and then blunt-ended. The whole sequence of the M_2 mutant (between *Nco*I and *Pst*I) was blunt-ended and then inserted into the vector (pGEX-M_2 mutant).

The pRGII/-MBP and pGEX based vectors were transformed into BL21, and the PET25(+ or –)-MBP-M_2 mutant and PET25b(+) based vectors were transformed into BL21 (DE3) and selected for ampicillin resistance. Also, for co-expression of thioredoxin, both the pRGII/MBP-M_2 mutant and pT-Trx were transformed into BL21(DE3) and selected for both ampicillin and chloramphenicol resistance. BL21 was grown in 2xTY medium containing 50 μg/ml ampicillin at 37°C until OD_{600} became 1.4. Then, the incubation temperature was reduced to 20°C and isopropyl β-thiogalactoside (IPTG) was added to 0.5 mM. The cells were harvested 24 h later and stored at –80°C. The M_2 mutant was expressed in Sf9/baculovirus, in the same manner as previously described (*5*, *10*).

Membrane Preparation—Spheroplasts were obtained by the method as described previously (*32*, *33*). The cell pellet derived from 1 liter culture was resuspended in 100 ml of a

Downloaded from http://jb.oxfordjournals.org/ at Cold Spring Harbor Laboratory on March 7, 2012

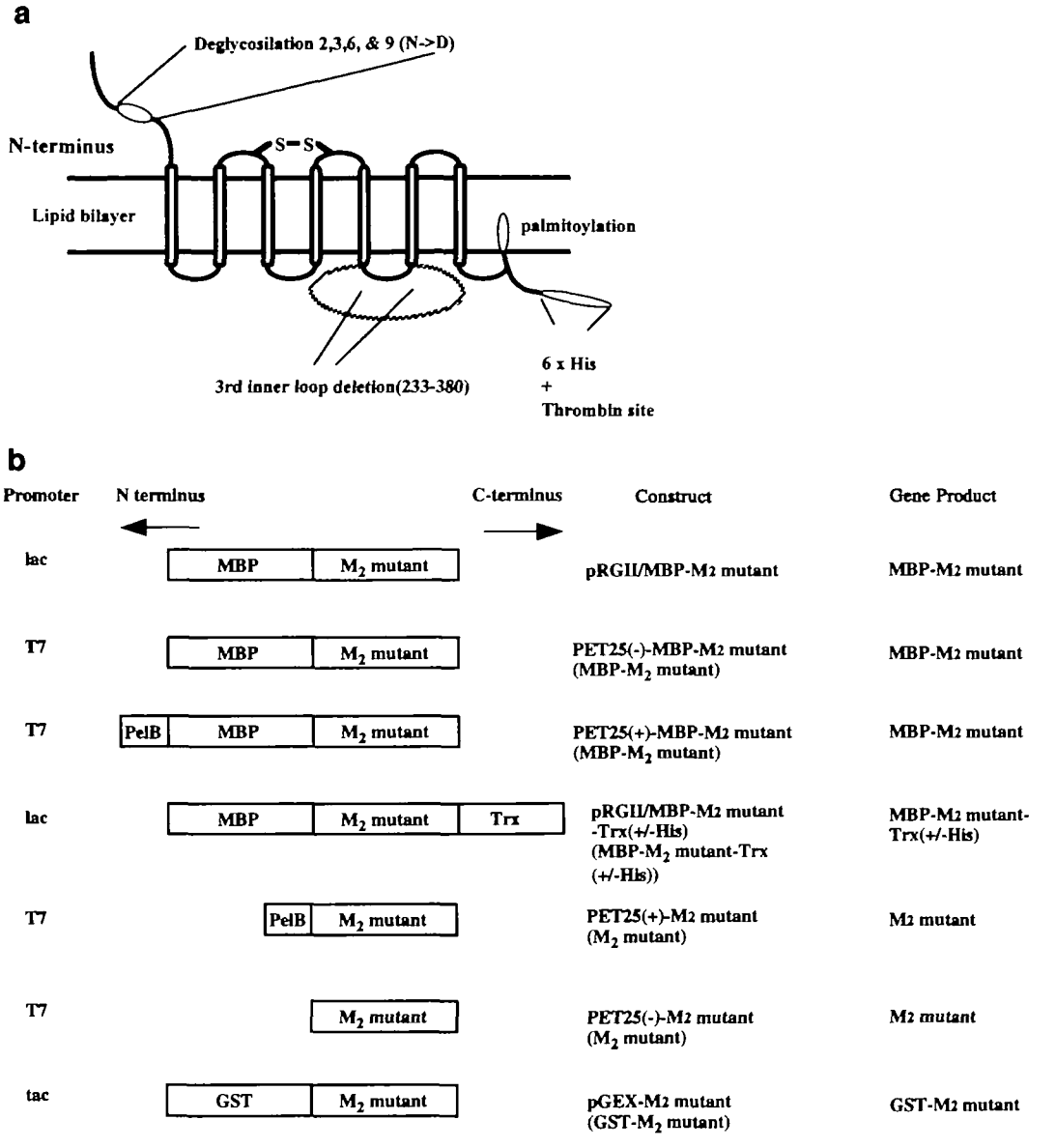

Fig. 1. **Topology of the M_2 mutant and the expression constructs.** (a) The mutations of the M_2 muscarinic receptor included deglycosilation at the N-terminal domain, deletion of the central part of the third inner loop, and the addition of a thrombin cleavage site and a 6×histidine tag. (b) Various fusion receptors with various promoters were obtained for expression.

buffer containing 20 mM Tris-HCl (pH 7.4), 1 mM EDTA, 25% sucrose, 0.5 mM phenylmethylsulphonyl fluoride, and 60 μg/ml lysozyme, and stirred at 4°C for 1 h. An equal amount of cold deionized water was added and then mild sonication was performed [30 s on and 2 min off at level 5 for three times, with a Tomy ultrasonic disruptor (UD-200)]. The membrane fraction was collected by centrifugation at 150,000 ×*g* at 4°C for 1 h. The pellet was resuspended in 100 ml of a buffer containing 20 mM Tris-HCl (pH 7.4), 500 mM NaCl, and 1 mM EDTA, and then centrifuged at 150,000 ×*g* at 4°C for 1 h. The pellet obtained on the last centrifugation was resuspended in 25 ml of 20 mM Tris-HCl (pH 7.4).

Ligand Binding Assay—The membrane fraction was assayed for its ability to bind to muscarinic antagonists, [^{3}H]QNB or [^{3}H] *N*-methylscopolamine ([^{3}H]NMS). The method for the binding assay was described previously (*34*). The membrane (20 μl from the above suspension) was incubated in 1 ml of 20 mM potassium phosphate buffer (KPB) (pH 7.0) containing [^{3}H]QNB or [^{3}H]NMS at 30°C for 1 h. [^{3}H]QNB or [^{3}H]NMS bound to receptors was trapped on a GF/B glass fiber filter and then the radioactivity was measured with a liquid scintillation counter.

The membrane fraction was solubilized with 1% digitonin and 0.3% sodium cholate at 2 mg/ml protein concentration. The solubilized receptor (10 μl) was incubated in 200 μl of a buffer containing 20 mM potassium phosphate buffer (pH 7.0), 100 mM NaCl, 0.1% digitonin and [^{3}H]QNB or [^{3}H]NMS at 30°C for 1 h with different concentrations of carbamylcholine and atropine. [^{3}H]QNB or [^{3}H]NMS bound

Downloaded from http://jb.oxfordjournals.org/ at Cold Spring Harbor Laboratory on March 7, 2012

to solubilized receptors was recovered in the void volume fraction from a Sephadex G50 column and then the radioactivity was measured with a liquid scintillation counter.

Western Blot Analysis—The MBP-M_2 mutant was solubilized with 1% Triton X100 at 4 mg/ml protein concentration. The solubilized fraction (30 µl) was subjected to SDS-PAGE on a 12% polyacrylamide gel and then transferred to a polyvinylidene difluoride membrane. After blocking with skim milk, the membrane was incubated with 0.05 µg/ml polyclonal antibodies against 6xHis, His-probe, followed by 0.4 µg/ml of goat anti rabbit IgG labeled with horseradish peroxidase. Bands were visualized by staining the membrane with dimethylaminoazobenzene.

Purification of the MBP-M_2 Mutant by Co^{2+}-Immobilized Chelating Sepharose Gel and Cation Exchange Chromatography—Co^{2+}-immobilized Chelating Sepharose gel was prepared by loading a 5× volume of 0.2 M $CoCl_2$ onto Chelating Sepharose gel. The solubilized MBP-M_2 mutant (100 ml), which was derived from 1 liter of culture and contained approximately 2 nmol of receptor, was loaded onto a 2 ml column volume of Co^{2+}-immobilized Chelating Sepharose gel at 30 ml/h. The column was washed with 20 ml of a buffer containing 20 mM Tris-HCl, 500 mM NaCl, 0.1% digitonin, and 10 mM imidazole (pH 7.4) at the same flow rate. The receptor was eluted with 10 ml of a buffer containing 50 mM imidazole buffer (pH 7.0), 500 mM NaCl, and 0.1% digitonin. The eluted fraction was diluted 20-fold with a buffer containing 10 mM Mes-KOH (pH 6.0) and 0.1% digitonin and loaded onto a 0.5 ml column volume of SP-Sepharose at approximately 30 ml/h. The column was washed with 5 ml of a buffer containing 10 mM Mes-KOH (pH 6.0), 50 mM NaCl, and 0.1% digitonin, and eluted with 2.5 ml of a buffer containing 20 mM Tris-HCl (pH 8.0), 300 mM NaCl, and 0.1% digitonin. The peak fraction was collected.

The M_2 mutant was purified by Co^{2+}-immobilized Chelating Sepharose gel essentially by the same method as above. The expression of the M_2 mutant in Sf9/baculovirus and the isolation of the membrane fraction were performed by means of the methods previously described (*5*).

Reconstitution of the MBP-M_2 Mutant and G Protein G_o or G_{i1}—The reconstitution method was essentially the same as that previously reported (*23*, *35*). G proteins were purified from porcine brain as described previously (*36*). Phosphatidylcholine (PC), phosphatidylinositol (PI), and cholesteryl hemisuccinate or PC and PI were dissolved in a chloroform and methanol solution [2:1 (v/v)] at 12:12:1 (w/w) or 1:1, respectively. The chloroform and methanol were evaporated off under constant N_2 aeration, and the resulting lipid film was suspended in a buffer containing 20 mM Hepes-KOH (pH 8.0), 1 mM EDTA, 160 mM NaCl (HEN), and 1% sodium cholate (Wako) at 4 mg/ml total lipid concentration. The purified MBP-M_2 mutant or the M_2 mutant (10 pmol) was mixed with 75 to 100 pmol of G_o or G_{i1} in 0.7% CHAPS in HEN supplemented with 20 mM $MgCl_2$, 10 mM DTT, 2 mg/ml of the lipid mixture and 1 mM carbamylcholine. The mixture (200 µl total volume) was run through Sephadex G50 pre-equilibrated with HEN. The void volume fraction was collected, and used as the reconstituted vesicles.

[^{3}H]QNB and [^{35}S]GTPγS Binding Assaying of the Reconstituted Receptor—The reconstituted vesicles were incubated with 1.5 nM [^{3}H]QNB at 30°C in HEN containing 10 mM $MgCl_2$ and 5 mM DTT with or without 100 µM GTP in the presence of various concentrations of carbamylcholine or atropine in a 1 ml total reaction volume. For the [^{35}S]GTPγS binding assay, the vesicles were incubated in HEN containing 10 mM $MgCl_2$, 1 mM DTT, 50 nM [^{35}S]GTPγS, and 5 µM GDP in the presence of 1 mM carbamylcholine or 10 µM atropine at 30°C for 0, 2, 5, 10, or 20 min. The total reaction volume was 100 µl. The reaction was stopped by the addition of 500 µl of HEN containing 100 µM GTP. In both the [^{3}H]QNB and [^{35}S]GTPγS binding assays, the vesicles after the reaction were trapped on GF/B glass fiber filters and then the radioactivity was measured with a liquid scintillation counter.

RESULTS

Expression of the MBP-M_2 Mutant—The expression levels of various fusion receptors are summarized in Table I. The M_2 mutant, rather than the wild type M_2 receptor, has been expressed because the wild type M_2 receptor tends to undergo degradation (most likely at the third intracellular loop region) during the purification process. Two strains of *E. coli*, BL 21 and DH 5, were examined for expression of the MBP-M_2 mutant under the same culture conditions. The expression level of the MBP-M_2 mutant was 1.5-fold higher in BL21 than in DH 5, so we used BL 21 throughout this work. The cells were grown at 37°C to a late growth

TABLE I. **Expression of the fusion M_2 mutants in *E. coli*.** Various constructs were examined for expression. In this study, the BL21 or BL21(DE3) strain was cultured in 2xTY medium containing 50 µg/ml ampicillin at 37°C until OD_{600} 1.4 was reached. The culture temperature was reduced to 20°C and expression was induced with 0.5 mM IPTG for 24 h. The membrane fraction was collected, and assayed for [^{3}H]QNB binding and subjected Western blotting with the His-probe. (+) or (–) for Western blotting corresponds to detection or non-detection of bands. Abbreviations: N.D., not determined; N.A. not applicable. *The induction was carried out for 4 h instead of 24 h. **Trx was co-expressed with the MBP-M_2 mutant.

Constructs	Promoters	Induction temperature (°C)	[^{3}H]QNB binding pmol/100 ml culture	Western blotting
MBP-M_2 mutant	*lac*	20	220 ± 40 (3)	+
		25	115 ± 14 (2)	N.D.
		37*	3 ± 0 (2)	N.D.
MBP-M_2 mutant–Trx(+His)	*lac*	20	188 ± 15 (2)	+
MBP-M_2 mutant–Trx(–His)	*lac*	20	202 ± 32 (2)	N.A.
MBP-M_2 mutant+Trx**	*lac*	20	200 ± 10 (2)	+
MBP-M_2 mutant	T7	20	92 ± 16 (2)	+
pelB-MBP-M_2 mutant	T7	20	85 ± 14 (2)	+
pelB-M_2 mutant	T7	20	0	–
M_2 mutant	T7	20	0	–
GST-M_2 mutant	*tac*	20	0	+

Downloaded from http://jb.oxfordjournals.org/ at Cold Spring Harbor Laboratory on March 7, 2012

phase (OD_{600} = 1.4), and incubated with 0.5 mM IPTG at 20°C for 24 h to induce the expression of the MBP-M_2 mutant. This culturing condition gave the best yield of the MBP-M_2 mutant among the conditions examined, such as those on induction of the expression at a lower cell density and for a longer time (Fig. 2). The membrane fraction derived from 100 ml of culture exhibited 0.2 nmol [^{3}H]QNB binding sites (6 pmol/mg of protein). The expression level of the MBP-M_2 mutant decreased to 50% or less when the cells were treated with 0.5 mM IPTG at 25°C instead of 20°C. Very little [^{3}H]QNB binding activity (less than 5 pmol in 100 ml of culture) was observed when the cells were treated with 0.5 mM IPTG at 37°C for 4 h. The co-expression of Trx, which was derived from the *E. coli* K 12 strain, did not improve the expression level of the MBP-M_2 mutant. The fusion of Trx or 6xHis and Trx to the C-terminus of the MBP-M_2 mutant was also not effective in increasing the expression level. This is in contrast with in the case of the neurotensin receptor, whose expression level was reported to increase on fusion of Trx to the C-terminus (*17*). The expression level of the MBP-M_2 mutant under the T7 promoter in the BL 21(DE3) strain was 2-fold lower compared to that of the MBP-M_2 mutant under the lac promoter in the BL 21 strain. The expression of the M_2 mutant without MBP fusion was not detected in the [^{3}H]QNB binding assay for the membrane preparation of *E. coli*. The expression of the MBP-M_2 mutant was further verified by Western blotting with polyclonal antibodies against 6xHis. A clear band appeared approximately at the position of the expected molecular weight (approximately 80 kDa) (Fig. 3). No band for the M_2 mutant was detected for the membrane preparation of *E. coli*, while a band was detected for the M_2 mutant from Sf9. Expression of the GST-M_2 mutant was observed on Western blotting, but no [^{3}H]QNB binding activity was detected (data not shown).

Solubilization and Purification of the MBP-M_2 Mutant from E. coli and the M_2 Mutant from Sf9 Cells—The MBP-M_2 mutant was solubilized with a buffer containing 1% digitonin and 0.3% sodium cholate at the protein concentration of 2 mg/ml. Eighty to ninty percent of the MBP-M_2 mutant was extracted from the membrane fraction, as assessed as [^{3}H]QNB binding activity. The MBP-M_2 mutant was purified on Co^{2+}-immobilized Chelating Sepharose gel and SP-Sepharose. Twenty-five to 40% of the [^{3}H]QNB binding activity in the solubilized fraction was recovered after the purification. The MBP-M_2 mutant was purified 100-fold and the specific activity increased from 5.0–6.5 to 420–650 pmol/mg protein. The M_2 mutant expressed in Sf9 cells was purified by the same method with a similar recovery (30–40% of the [^{3}H]QNB binding activity in the solubilized fraction), and the specific activity increased from 50–68 to 4,500–6,500 pmol/mg of protein.

Ligand Binding Properties of the MBP-M_2 Mutant Compared with the M_2 Mutant—Ligand binding properties were compared between solubilized preparations of the MBP-M_2 mutant and the M_2-mutant, which were derived from *E. coli* and Sf9 cells, respectively. Both the MBP-M_2 mutant and the M_2 mutant showed high affinity for [^{3}H]QNB and [^{3}H]NMS (Fig. 4). From Scatchard plots, the K_d and B_{max} values for [^{3}H]QNB and [^{3}H]NMS were calculated for the MBP-M_2 mutant and the M_2 mutant (Table II). Figure 5 shows displacement curves of [^{3}H]QNB binding for carbamylcholine (muscarinic agonist) and atropine (muscarinic antagonist). The K_i values for carbamylcholine and atropine were calculated from the displacement curve (Table II). Both the K_d and K_i values were very similar for the MBP-M_2 mutant and the M_2 mutant. These results indicate that the MBP-M_2 mutant expressed in *E. coli* has the same ligand binding activity as the M_2-mutant expressed in Sf9 cells, and that the addition of MBP at the N-terminus of the M_2 mutant does not alter the ligand binding properties.

Interaction of the MBP-M_2 Mutant with G Protein G_o and G_{i1}—We examined the ability of the MBP-M_2 mutant to interact with G protein G_o and compared it with that of the M_2 mutant. The purified MBP-M_2 mutant and the M_2 mutant were reconstituted with purified G protein G_o or G_{i1} in

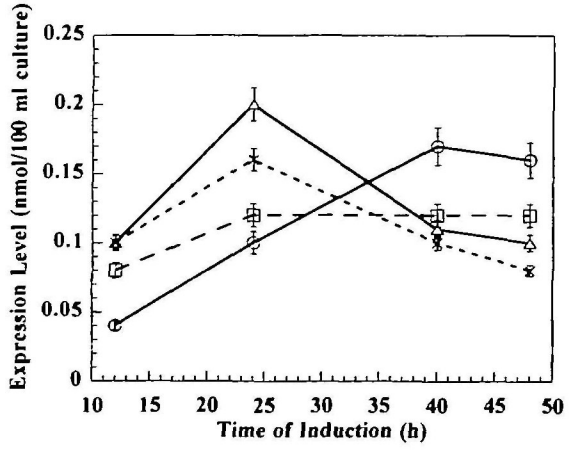

Fig. 2. **Culture conditions and expression levels.** Induction with 0.5 mM IPTG was carried out at various OD_{600} values (◇ = 0.6, □ = 1.0, △ = 1.4, × = 1.8) and for various lengths of time. The graph shown is representative of two experiments.

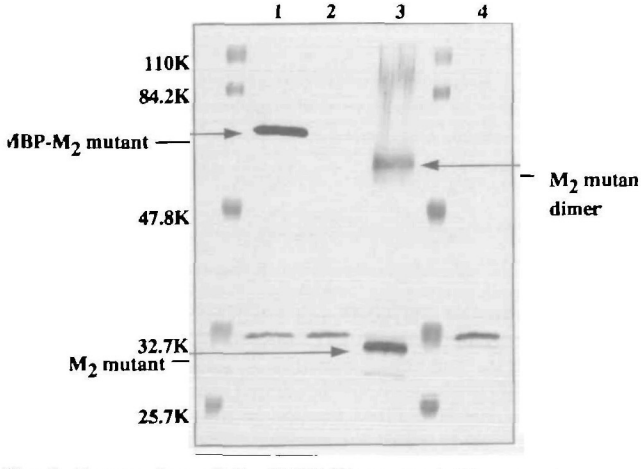

Fig. 3. **Expression of the MBP-M_2 mutant.** The receptors were solubilized with 1% Triton X-100 at 4 mg/ml protein concentration. The solubilized fraction (30 and 3 μl per lane for the preparation derived from *E. coli* and Sf9, respectively) was subjected to SDS-PAGE followed by Western blotting with polyclonal antibodies for the 6×histidine tag. The MBP-M_2 mutant from *E. coli* (lane 1) and the M_2 mutant from Sf9 (lane 3) have theoretical molecular weights of approximately 80 and 35 kDa, respectively. No expression of the M_2 mutant was observed in *E. coli* (lane 4). Lane 2 represents a control that contained the vector without the M_2 mutant gene.

Downloaded from http://jb.oxfordjournals.org/ at Cold Spring Harbor Laboratory on March 7, 2012

lipid vesicles consisting of PC, PI, and cholesteryl hemisuccinate. Figure 6 shows displacement curves for carbamylcholine or atropine as to [^{3}H]QNB binding of the reconstituted vesicles in the presence or absence of 0.1 mM GTP. For both the MBP-M_2 mutant and the M_2 mutant, the displacement curves with carbamylcholine were biphasic in the absence of GTP and monophasic in the presence of GTP. The displacement curves with atropine for both the MBP-mutant and the M_2 mutant were monophasic in either the presence or absence of GTP. The displacement curves with carbamylcholine in the absence of GTP well fitted the equation for a two-binding site model whereas the rest of the displacement curves well fitted the equation for a one-binding site model. The percentages and K_i values of the high and low affinity sites were calculated from the displacement curves (Table III). The results are consistent with the previous data obtained on reconstitution of G proteins with the M_2 muscarinic receptor purified from porcine atria (*37*, *38*) or the M_2 mutant from Sf9 cells (*10*), and can be explained with the same assumption; the M_2 muscarinic receptor interacts with G_o in the absence of GTP and the M_2-G_o complex exhibits higher affinity for carbamylcholine than the free M_2 receptor, whereas M_2-G_o and M_2 exhibit the same affinity for atropine. The similarity in the proportions of high affinity sites in the absence of GTP indicate that the MBP-M_2 mutant from *E. coli* has the same ability to couple with G protein G_o as the M_2 mutant from Sf9 (*10*). In addition, the similarity in K_i values of carbamylcholine and atropine indicates that the MBP-M_2 mutant expressed in *E. coli* and the M_2 mutant from Sf9 cells have essentially the same characteristics as to interaction with both ligands and G proteins.

The MBP-M_2 mutant was then examined as to its ability to activate G_o by measuring the agonist-dependent [^{35}S]-GTPγS binding activity for the reconstituted vesicles (Fig. 7). The vesicles were incubated with 50 nM [^{35}S]GTPγS in

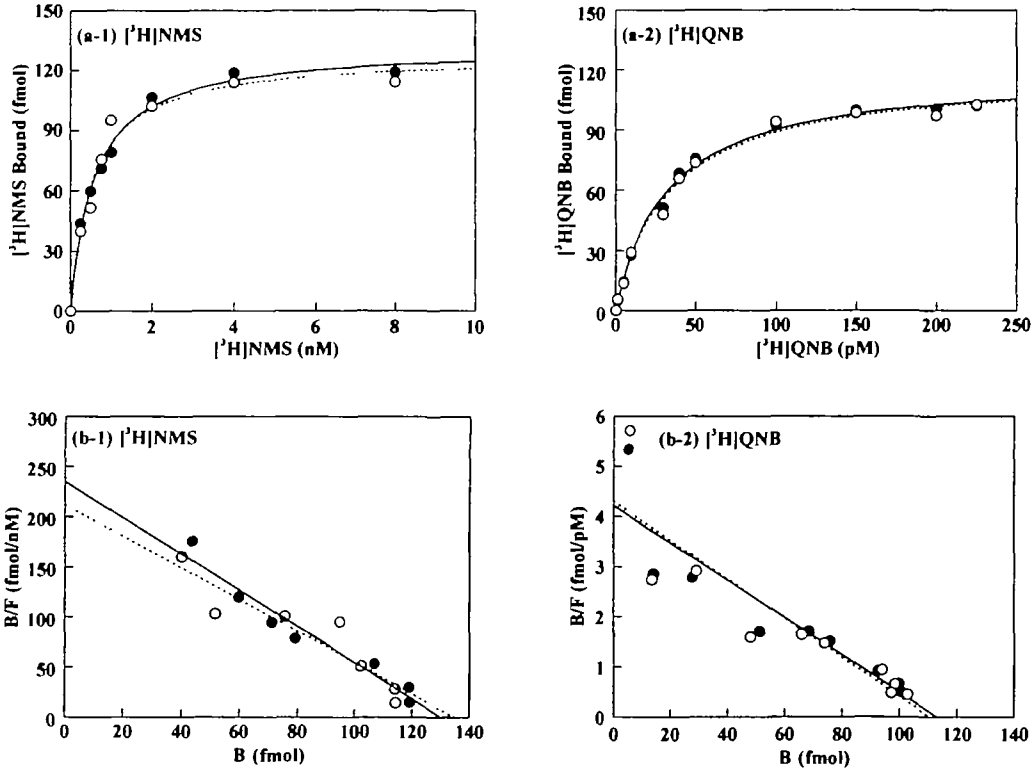

Fig. 4. **Binding of [^{3}H]QNB and [^{3}H]NMS with the MBP-M_2 mutant from *E. coli* and the M_2 mutant from Sf9 cells.** The *E. coli* (◆, solid lines) and Sf9 (◇, dotted lines) membrane fractions were solubilized with 1% digitonin/0.3% sodium cholate at 2 mg/ml protein concentration. The solubilized fraction of the M_2 mutant from Sf9 was diluted 10-fold to adjust the receptor concentration to that of the MBP-M_2 mutant. Ten microliters each of these fractions was incubated with various concentrations of [^{3}H]NMS (a-1) or [^{3}H]QNB (a-2) in 200 μl of a buffer containing 20 mM potassium phosphate buffer (pH 7.0), 0.1 M NaCl, and 0.1% digitonin at 30°C for 1 h. Each point represents the average of values determined in duplicate in two different experiments (b-1 and b-2). Scatchard transformation of data in (a-1) and (a-2).

TABLE II. **Affinity of [^{3}H]NMS and [^{3}H]QNB for the MBP-M_2 mutant and the M_2 mutant.** The K_d and B_{max} values for [^{3}H]NMS and [^{3}H]QNB were calculated from Scatchard plots for the MBP-M_2 mutant and the M_2 mutant in Fig. 4.

	K_d (pM) [^{3}H]QNB	K_d (nM) [^{3}H]NMS	B_{max} (fmol/20 μg protein) [^{3}H]QNB	B_{max} (fmol/20 μg protein) [^{3}H]NMS	K_i (nM) Atropine	K_i (μM) Carbamylcholine
MBP-M_2 mutant (*E. coli*)	27.1	1.80	113	130	0.44	46.2
M_2 mutant (Sf9)	25.7	1.57	111	135	0.30	25.2

Downloaded from http://jb.oxfordjournals.org/ at Cold Spring Harbor Laboratory on March 7, 2012

the presence of 5 μM GDP and carbamylcholine or atropine. For both the MBP-M_2 mutant and the M_2 mutant, the extent of [^{35}S]GTPγS binding was greater in the presence of carbamylcholine than in the presence of atropine. These results are also consistent with the previous ones obtained for the M_2 receptor derived from mammalian tissues (*37*, *38*) or Sf9 cells (*10*), and indicate that the agonist-bound MBP-M_2 mutant can facilitate the binding of [^{35}S]GTPγS to G_o in the presence of GDP in the same way as the M_2 mutant.

The MBP-M_2 mutant was also shown to interact with and activate G protein G_{i1}. Figure 8a shows the [^{3}H]QNB binding activity of the reconstituted vesicles of the MBP-M_2 mutant and G_{i1} in the presence of various concentrations of carbamylcholine and atropine, and in the presence or absence of 0.1 mM GTP. As with G protein G_o, the displacement curve with carbamylcholine in the absence of GTP well fitted the equation for a two-binding site model whereas the rest of the displacement curves well fitted the equation for a one-binding site model. The percentages and K_i values of the high and low affinity sites were calculated from the displacement curves (Table III). The ability of the MBP-M_2 mutant to activate G_{i1} was also demonstrated as stimulation by carbamylcholine of the [^{35}S]GTPγS binding activity of the reconstituted vesicles in the presence of GDP (Fig. 8b).

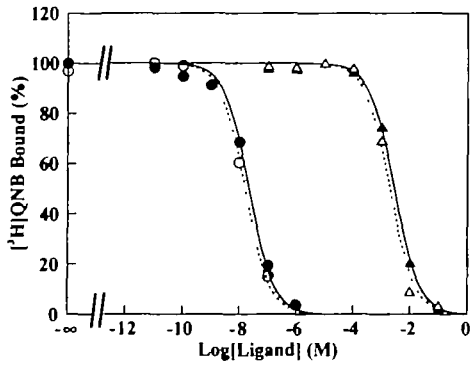

Fig. 5. **Displacement of [^{3}H]QNB by carbamylcholine and atropine.** The experimental conditions were the same as those given in the legend to Fig. 3, except that a single concentration of [^{3}H]QNB (1.5 nM), and different concentrations of carbamylcholine (△, ▲) and atropine (◇, ◆) were incubated with the solubilized MBP-M_2 mutant (▲, ◆, solid lines) and M_2 mutant (△, ◇, dotted lines). The graphs shown are each representative of four experiments. The actual value for 100% is 5,000 to 6,000 dpm.

Figure 9 shows the displacement curves for GDP of [^{35}S]GTPγS binding in the presence of carbamylcholine or

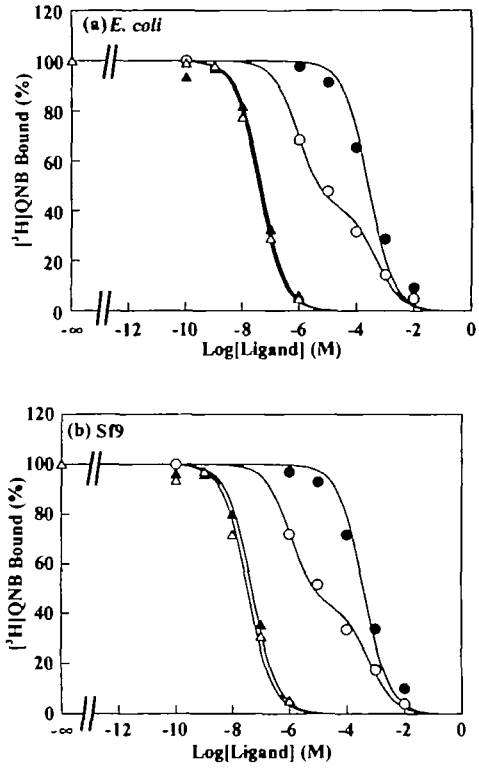

Fig. 6. **Interaction of the MBP-M_2 mutant and the M_2 mutant with G protein G_o.** The MBP-M_2 mutant (a) and the M_2 mutant (b) were solubilized from *E. coli* and Sf9 membranes, respectively, purified, and then reconstituted into lipids with G_o purified from porcine brain. The reconstituted vesicles containing 100 fmol of the MBP-M_2 mutant or the M_2 mutant in a 50 μl volume were incubated with 950 μl of buffer containing 1.5 nM [^{3}H]QNB in the presence of carbamylcholine (◇ , ◆) or atropine (△ , ▲), and in the presence (▲ , ◆) or absence (△ , ◇) of 0.1 mM GTP at 30°C for 1 h. Displacement curves in the presence of carbamylcholine and in the absence of GTP well fitted the equation for a two-site model whereas the rest of the displacement curves well fitted the equation for a one-site model. The equation for the two-site model was $Y = A*IC_{50}(L)/(X + IC_{50}(L)) + (100 - A)IC_{50}(H)/(X + IC_{50}(H))$, where A is the percentage of low-affinity sites, $IC_{50}(H)$ and $IC_{50}(L)$ the concentrations of carbamylcholine giving half-maximal effects on the [^{3}H]QNB as to the high- and low-affinity sites, respectively, and X the concentration of carbamylcholine. The equation for the one-site model was $Y = 100*IC_{50}/(X + IC_{50})$. The graphs shown are each representative of four experiments.

TABLE III. **Affinity of carbamylcholine and atropine for the MBP-M_2 mutant and the M_2 mutant reconstituted with G proteins.** The K_i values for carbamylcholine and atropine were calculated from the data in Figs. 6, 7, and 9. Abbreviations: (H), high-affinity binding site; (L), low-affinity binding site.

	K_i (atropine) GTP(−)	K_i (atropine) GTP(+)	K_i (carbamylcholine) GTP(−) K_i (H)	K_i (carbamylcholine) GTP(−) K_i (L) (%)	GTP(+)	Proportion of high-affinity sites (%)
MBP-M_2 mutant-G_o (*E. coli*) (PC/PI/Cholesterol)	0.69	0.85	15.3	7.99	4.34	58.7
M_2 mutant-G_o (Sf9) (PC/PI/Cholesterol)	0.84	0.59	18.9	10.0	6.60	56.8
MBP-M_2 mutant-G_o (*E. coli*) (PC/PI)	—	—	21.5	6.76	14.1	58.7
MBP-M_2 mutant-G_{i1} (*E. coli*) (PC/PI/Cholesterol)	0.77	0.65	134.0	7.43	7.2	68.8

Downloaded from http://jb.oxfordjournals.org/ at Cold Spring Harbor Laboratory on March 7, 2012

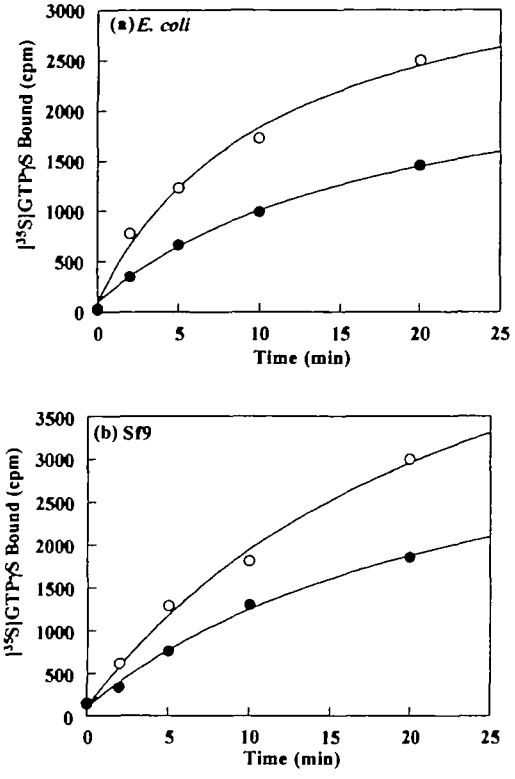

Fig. 7. **Stimulation of [^{35}S]GTPγS binding to G protein G_o reconstituted with the MBP-M_2 mutant or the M_2 mutant.** G_o and the MBP-M_2 mutant from *E. coli* (a) or the M_2 mutant from Sf9 (b) were reconstituted into lipids as described in the legend to Fig. 5. The reconstituted vesicles containing 100 fmol of the MBP-M_2 mutant or the M_2 mutant were incubated with 50 nM [^{35}S]GTPγS and 5 μM GDP in the presence of 1 mM carbamylcholine (◇) or 10 μM atropine (●). The graphs shown are each representative of four experiments.

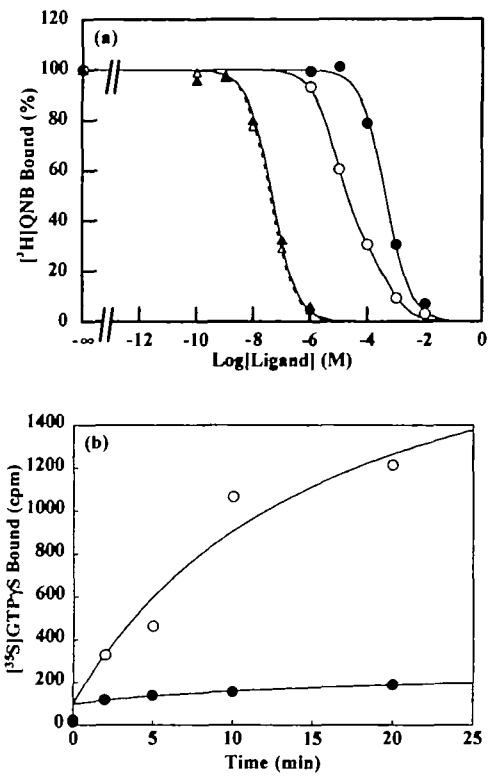

Fig. 8. **Interaction of the MBP-M_2 mutant with and stimulation of [^{35}S]GTPγS binding to G protein G_{i1}.** The MBP-M_2 mutant was reconstituted into lipids with G_{i1} purified from porcine brain. The reconstituted vesicles containing 100 fmol of the MBP-M_2 mutant or the M_2 mutant in a 50 μl volume were incubated with 950 μl of buffer containing 1.5 nM [^{3}H]QNB in the presence of carbamylcholine (◇, ◆) or atropine (△, ▲), and in the presence (▲, ◆) or absence (△, ◇) of 0.1 mM GTP at 30°C for 1 h. Curve fitting was performed as described in the legend to Fig. 5 (a). The reconstituted vesicles containing 100 fmol of the MBP-M_2 mutant were incubated with 50 nM [^{35}S]GTPγS and 5 μM GDP in the presence of 1 mM carbamylcholine (◇) or 10 μM of atropine (◆) (b). The graphs shown are each representative of three experiments.

atropine for reconstituted vesicles of the MBP-M_2 mutant with G_o or G_{i1}. In vesicles containing either G_o or G_{i1}, the displacement curves in the presence of carbamylcholine shifted to the right compared to the ones in the presence of atropine. The IC_{50} values of GDP in the presence of carbamylcholine and atropine were estimated to be 4.11 and 0.24 μM for G_{i1}, and 37.2 and 2.04 μM for G_o, respectively. The differences in IC_{50} values between carbamylcholine and atropine were 17.1-fold in G_{i1} and 18.2-fold in G_o. These results indicate that the agonist-bound receptor exhibits 17–19 fold lower affinity for GDP than the antagonist-bound receptor, and that the carbamylcholine-bound MBP-M_2 mutant interacts with both G_o and G_{i1}.

Effect of Cholesterol on the Interaction of the MBP-M_2 Mutant with G Protein G_o—The MBP-M_2 mutant and G protein G_o were reconstituted into lipid vesicles without cholesteryl hemisuccinate. The displacement of [^{3}H]QNB binding by carbamylcholine was assessed in the same way as described previously. The displacement curve in the presence of GTP well fitted the equation for a one-binding site model, whereas that in the absence of GTP well fitted the equation for a two-binding site model (Fig. 10a). The percentages and K_i values of the high and low affinity sites were calculated from the displacement curves (Table III). The similarity in the percentages and K_i values showed that the MBP-M_2 mutant reconstituted into cholesterol-containing vesicles and cholesterol-free vesicles had the same ability to associate with G protein G_o.

The reconstituted vesicles were also examined as to their ability to bind [^{35}S]GTPγS in the presence of carbamylcholine or atropine as described previously. In both cholesterol-containing (Fig. 7a) and cholesterol-free vesicles (Fig. 10b), the extent of [^{35}S]GTPγS binding was greater in the presence of carbamylcholine than in the presence of atropine. These results indicate that cholesterol is not required for the MBP-M_2 mutant to interact with and activate G protein G_o.

DISCUSSION

In this study, we have shown that the MBP-M_2 mutant expressed in *E. coli* has the ability to interact with both muscarinic ligands and G proteins G_o and G_{i1}.

Fusion of MBP was necessary for functional expression. The MBP could not be replaced by GST or a leader sequence, pelB. Expression of the pel B-M_2 mutant was not detected on Western blotting while expression of the GST-

Downloaded from http://jb.oxfordjournals.org/ at Cold Spring Harbor Laboratory on March 7, 2012

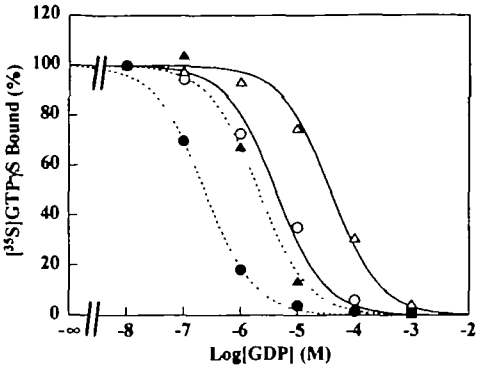

Fig. 9. **Displacement of [^{35}S]GTPγS by GDP in the presence of carbamylcholine or atropine.** The MBP-M_2 mutant was reconstituted into lipids with G protein G_o or G_{i1} as described in the legend to Fig. 5. The reconstituted vesicles containing 100 fmol of the MBP-M_2 mutant were inc ubated with 50 nM [^{35}S]GTPγS (15,000 cpm/50 μl reaction buffer) and various concentrations of GDP in the presence of 1 mM carbamylcholine (○, △) or 10 μM atropine (◆, ▲) at 30°C for 30 min. The graphs shown are each representative of three experiments. (▲, △) represent the data points for G_o, and (◆, ○) these for G_{i1}.

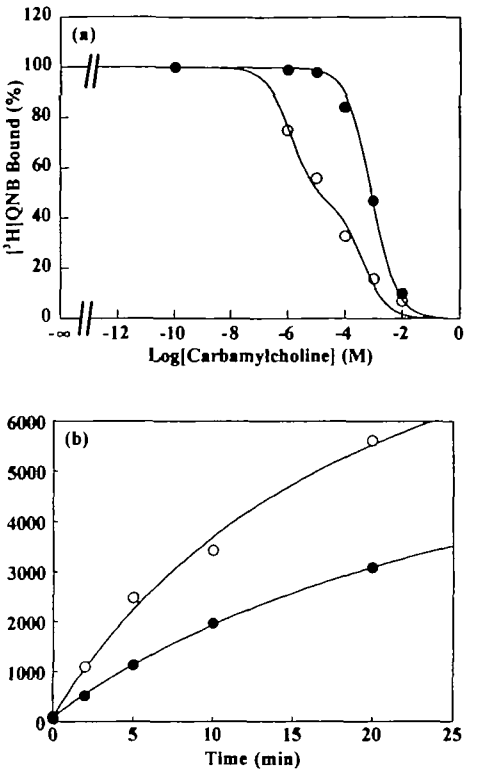

Fig. 10. **Interaction of the MBP-M_2 mutant with and stimulation of [^{35}S]GTPγS binding to G protein G_o in the absence of cholesterol.** The MBP-M_2 mutant and G_o were reconstituted into lipids consisting of phosphatidylcholine and phosphatidylinositol [50:50(w/w)] only. The experimental conditions were the same as those given in the legend to Fig. 5, except that cholesteryl hemisuccinate was omitted. Incubation was carried out in the presence (◆) or absence (○) of 0.1 mM GTP (a). The reconstituted vesicles containing 100 fmol of the MBP-M_2 mutant were incubated with 50 nM [^{35}S]GTPγS and 5 μM GDP in the presence of 1 mM carbamylcholine (○) or 10 μM atropine (◆) (b). The graphs shown are each representative of four experiments.

M_2 mutant was detected on Western blotting, but no [^{3}H]QNB binding activity was detected. These results suggest that fusion of a periplasmic protein, MBP, but not a cytosolic protein, GST, is required for the membrane translocation and proper folding of the M_2 receptor in membranes. MBP is secreted in a SecB-dependent manner and the MBP fusion receptor is thought to manipulate this secretional machinery to translocate itself to the *E. coli* inner membrane (*30*). The expression level was sensitive to the induction temperature; a low induction temperature is necessary as in the case of the neurotensin receptor (*16*) or cytochrome b_5 (*39*). In addition, the use of different promoters resulted in different expression levels. The expression level of the MBP-M_2 mutant under the T7 promoter (PET25b) was half that of the MBP-M_2 mutant under the lac promoter when cells were cultured under the same conditions. The lac promoter is a much weaker promoter than the T7 promoter. The preference for a low temperature and a weaker promoter implies that a slow transcription rate is critical for expression of a great amount of functional receptors. This is consistent with the suggestion of Grisshammer and Tate that slow transcription is essential for proper folding of the MBP-neurotensin fusion receptor into membranes (*13*).

Other GPCRs such as the substance K receptor (*40*) and the M_1 muscarinic receptor (*18*) have been reported to be expressed functionally in terms of ligand binding activity on fusion of MBP to their N-termini. To our knowledge, however, the MBP fusion receptors including the neurotensin receptor have not been examined as to their ability to interact with G proteins. In the present study, we solubilized and partially purified the MBP-M_2 mutant, and reconstituted it with purified G protein G_o or G_{i1} into phospholipids vesicles. Using the reconstituted vesicles, we have provided direct evidence that the MBP-M_2 mutant expressed in *E. coli* retains the ability to interact with and activate G_o and G_{i1}, and that there is virtually no difference in the affinity for muscarinic ligands and the ability to interact with G_o between the MBP-M_2 mutant and the M_2 mutant expressed in the Sf9-baculovirus system. We have already shown that the M_2 mutant expressed in Sf9 cells has the same ability to interact with muscarinic ligands and G proteins as the wild type M_2 muscarinic receptor purified from porcine atria (*10*). Thus, we conclude that the MBP-M_2 mutant has the same ability as the mammalian M_2 receptor. *E. coli* will be the simplest and the least expensive means of producing functionally active GPCRs.

The M_2 mutant expressed in Sf9 cells has been shown to be palmitoylated at cysteine residue in its C-terminal tail (*41*). Although palmitoylation at cysteine residues has not been observed in *E. coli*, the MBP-M_2 mutant from *E. coli* showed the same ability to interact with G proteins as the M_2 mutant from Sf9 cells. This indicates that palmitoylation is not necessary for the function of the muscarinic receptor. On the other hand, the M_2 mutant, whose relevant cysteine residue is substituted with an alanine residue, showed the ability to interact with and activate G protein G_{i2}, but with less activating ability than the palmitoylated receptor (*41*). Several explanations for this discrepancy are possible, as follows. One explanation is that the reduced ability of the M_2 mutant was caused by replacement of the cysteine residue by an alanine residue, but not

Downloaded from http://jb.oxfordjournals.org/ at Cold Spring Harbor Laboratory on March 7, 2012

by the lack of palmitoylation. Another possible explanation is that the unpalmitoylated receptor purified from Sf9 cells is less stable and is recovered in a lower yield on reconstitution compared to the palmitoylated receptor, whereas the unpalmitoylated receptor purified from *E. coli* is stable and recovered in the same yield as the palmitoylated receptor. In this respect, it should be noted that the degree of purification was ten times higher for the M_2 mutant from Sf9 cells than the MBP-M_2 mutant from *E. coli*, and that the highly purified receptor becomes more unstable during the reconstitution procedure than the less purified receptor. The present finding is compatible with the report that the function of the M_2 mutant in Chinese hamster ovary (CHO) cells is not affected by the presence or absence of palmitoylation (*42*).

Lipids of *E. coli* membranes comprise 70% phosphatidylethanolamine, 15% phosphatidylglycerol, and 15% cardiolipin (w/w), and are different from those of mammalian or Sf9 cell membranes, particularly in that they do not contain cholesterol (*29*). The present results suggest that the function of the M_2 receptor is not affected by lipid environment of membranes. Our results provide direct evidence that choresterol is not required for the interaction of the M_2 muscarinic receptor with muscarinic ligands and G proteins. Strictly speaking, we cannot exclude the possibility that cholesterol was copurified with G proteins which were purified from porcine brain. This, however, is not likely because G proteins are not integral membrane proteins with transmembrane segments.

In summary, we have shown that the functional M_2 muscarinic receptor can be expressed in *E. coli* when MBP is fused to its N-terminus. The MBP-fused receptor possesses the same ligand binding activity and ability to interact with G proteins as the M_2 muscarinic receptor expressed in Sf9 cells. We have also shown that cholesterol and palmitoylation are not essential for the function of the muscarinic receptor.

We wish to thank Dr. R. Grisshammer for the pRG/II-MBP vector; Dr. S. Ishii for the pT-Trx vectors; Dr. K. Shiozaki for the G protein G_o and G_{i1}; Dr. Hayashi for the Puc19-M_2 mutant; Dr. K. Haga for the help in the receptor reconstitution, and Dr. Touhara for the help in the DNA work and discussions.

REFERENCES

1. Gether, U. and Kobilka, B.K. (1998) G protein-coupled receptors. *J. Biol. Chem.* **273**, 17979–17982
2. Lefkowitz, R.J. (1998) G protein-coupled receptors. *J. Biol. Chem.* **273**, 18677–18680
3. Wess, J., Liu, J., Blin, N., Yun, J., Lerche, C., and Kostenis, E. (1997) Structural basis of receptor G protein coupling selectivity studied with muscarinic receptors as model systems. *Life Sci.* **60**, 1007–1014
4. Hulme, E. C., Birdsall, N.J., and Buckley, N.J. (1990) Muscarinic receptor subtypes. *Annu. Rev. Pharmacol. Toxicol.* **30**, 633–673
5. Parker, E.M., Kameyama, K., Higashijima, T., and Ross, E.M. (1991) Reconstitutively active G protein-coupled receptors purified from baculovirus-infected insect cells. *J. Biol. Chem.* **266**, 519–527
6. Hartman IV, J.L. and Northup, J.K. (1996) Functional reconstitution *in situ* of 5-hydroxytryptamine$_{2C}$ ($5HT_{2C}$) receptors with αq and inverse agonism of $5HT_{2c}$ receptor antagonists. *J. Biol. Chem.* **271**, 22591–22597
7. Heitz, F., Nay, C., and Guenet, C. (1997) Expression of functional human muscarinic M_2 receptors in different insect cell lines. *J. Recept. Sig. Trans. Res.* **17**, 305–317
8. Ross, S.M., Taverna, F.A., Pickering, D.S., Wang, L-Y., MacDonald, J.F., Pennefather, P.S., and Hampson, D.R. (1994) Expression of functional metabotropic and ionotropic glutamate receptors in baculovirus-infected insect cells. *Neurosci. Lett.* **173**, 139–142
9. Guo, Z.D., Kameyama, K., Rinken, A., and Haga, T. (1995) Ligand binding properties of muscarinic acetylcholine receptor subtypes (m1–m5) expressed in baculovirus-infected insect cells. *J. Pharmacol. Exp. Ther.* **274**, 378–384
10. Hayashi, M.K. and Haga, T. (1996) Purification and functional reconstitution with GTP-binding regulatory proteins of hexahistidine-tagged muscarinic acetylcholine receptors (m2 subtype). *J. Biochem.* **120**, 1232–1238
11. Payette, P., Gossard, F., Whiteway, M., and Dennis, M. (1990) Expression and pharmacological characterization of the human M1 muscarinic receptor in *Saccharomyces cerevisiae*. *FEBS Lett.* **266**, 21–25
12. Mu, J.H., Chua, N.H., and Ross, E.M. (1997) Expression of human muscarinic cholinergic receptors in tobacco. *Plant Mol. Biol.* **34**, 357–362
13. Grisshammer, R. and Tate, C.G. (1995) Overexpression of integral membrane proteins for structural studies. *Q. Rev. Biophys.* **28**, 315–422
14. Marullo, S., Delavier-Klutchko, C., Eshdat, Y., Strosberg, D.A., and Emorine, L. (1988) Human β2-adrenergic receptors expressed in *Escherichia coli* membranes retain their pharmacological properties. *Proc. Natl. Acad. Sci. USA* **85**, 7551–7555
15. Bertin, B., Freissmuth, M., Breyer, R.M., Schutz, W., Strosberg, A.D., and Marullo, S. (1992) Functional expression of the human serotonin 5-HT1A receptor in *Escherichia coli*. Ligand binding properties and interaction with recombinant G protein alpha-subunits. *J. Biol. Chem.* **267**, 8200–8206
16. Grisshammer, R., Duckworth, R., and Henderson, R. (1993) Expression of a rat neurotensin receptor in *Escherichia coli*. *Biochem. J.* **295**, 571–576
17. Tucker, J. and Grisshammer, R. (1996) Purification of a rat neurotensin receptor expressed in *Escherichia coli*. *Biochem. J.* **317**, 891–899
18. Hulme, E.C. and Curtis, C.A.M. (1998) Purification of recombinant M1 muscarinic acetylcholine receptor. *Biochem. Soc. Trans.* **26**(4), S361
19. Yeagle, P.L. (1985) Cholesterol and the cell membrane. *Biochim. Biophys. Acta* **822**, 267–287
20. Rankin, S.E., Addona, G.H., Kloczewiak, M.A., Bugge, B., and Miller, K.W. (1997) The cholesterol dependence of activation and fast desensitization of the nicotinic acetylcholine receptor. *Biophys. J.* **73**, 2446–2455
21. Dreger, M., Krauss, M., Herrmann, A., and Hucho, F. (1997) Interactions of the nicotinic acetylcholine receptor transmembrane segments with the lipid bilayer in native receptor-rich membranes. *Biochemistry* **36**, 839–847
22. Kirilovsky, J. and Schramm, M. (1983) Delipidation of a beta-adrenergic receptor preparation and reconstitution by specific lipids. *J. Biol. Chem.* **258**, 6841–6849
23. Berstein, G., Haga, T., and Ichiyama, A. (1989) Effect of the lipid environment on the differential affinity of purified cerebral and atrial muscarinic acetylcholine receptors for pirenzepine. *Mol. Pharmacol.* **36**, 601–607
24. Gimpl, G., Klein, U., Reilander, H., and Fahrenholz, F. (1995) Expression of the human oxytocin receptor in baculovirus-infected insect cells: high-affinity binding is induced by a cholesterol-cyclodextrin complex. *Biochemistry* **34**, 13794–13801
25. Klein, U., Gimpl, G., and Fahrenholz, F. (1995) Alteration of the myometrial plasma membrane cholesterol content with beta-cyclodextrin modulates the binding affinity of the oxytocin receptor. *Biochemistry* **34**, 13784–13793
26. Klein, U. and Fahrenholz, F. (1994) Reconstitution of the myometrial oxytocin receptor into proteoliposomes. Dependence of oxytocin binding on cholesterol. *Eur. J. Biochem.* **220**, 559–567

Downloaded from http://jb.oxfordjournals.org/ at Cold Spring Harbor Laboratory on March 7, 2012

27. Maguire, P.A. and Druse, M.J. (1989) The influence of cholesterol on synaptic fluidity, dopamine D1 binding and dopamine-stimulated adenylate cyclase. *Brain Res. Bull.* **23**, 69–74
28. Mitchell, D.C., Straume, M., Miller, J.L., and Litman, B.J. (1990) Modulation of metarhodopsin formation by cholesterol-induced ordering of bilayer lipids. *Biochemistry* **29**, 9143–9149
29. Ambudkar, S.V. and Maloney, P.C. (1986) Anion exchange in bacteria: reconstitution of phosphate: hexose 6-phosphate antiport from *Streptococcus lactis*. *Methods Enzymol.* **125**, 558–563
30. Wickner, W., Driessen, A.J.M., and Hartl, F.-U. (1991) The enzymology of protein. Translocation across the *Escherichia coli* plasma membrane. *Annu. Rev. Biochem.* **60**, 101–124
31. Yasukawa, T., Kanei-Ishii, C., Maekawa, T., Fujimoto, J., Yamamoto, T., and Ishii, S. (1995) Increase of solubility of foreign proteins in *Escherichia coli* by coproduction of the bacterial thioredoxin. *J. Biol. Chem.* **270**, 25328–25331
32. Witholt, B., Boekhout, M., Brock, M., Kingma, J., Heerikhuizen, H.V., and Leij, L.D. (1976) *Anal. Biochem.* **74**, 160–170
33. Henderson, P.J.F. and MacPherson, A.J.S. (1986) *Methods Enzymol.* **125**, 387–429
34. Haga, T., Haga, K., and Hulme, E.C. (1990) *Receptor Biochemistry: A Practical Approach*, pp. 1–50, IRL Press, London
35. Shiozaki, K. and Haga, T. (1992) Effects of magnesium on the interaction of atrial muscarinic acetylcholine receptors and GTP-binding regulatory proteins. *Biochemistry* **31**, 10634–10642
36. Haga, K., Uchiyama, H., Haga, T., Ichiyama, A., Kangawa, K., and Matsuo, H. (1989) Cerebral muscarinic acetylcholine receptors interact with three kinds of GTP-binding proteins in a reconstitution system of purified components. *Mol. Pharmacol.* **35**, 286–294
37. Ikegaya, T., Nishiyama, T., Haga, K., Haga, T., Ichiyama, A., Kobayashi, A., and Yamazaki, N. (1990) Interaction of atrial muscarinic receptors with three kinds of GTP-binding proteins. *J. Mol. Cell Cardiol.* **22**, 343–351
38. Tota, M.R., Kahler, K.R., and Schimerlik, M.I. (1987) Reconstitution of the purified porcine atrial muscarinic acetylcholine receptor with purified porcine atrial inhibitory guanine nucleotide binding protein. *Biochemistry* **26**, 8175–8182
39. Holmans, P.L., Shet, M.S., Martin-Wixtrom, C.A., Fisher, C.W., and Estabrook, R.W. (1994) The high-level expression in *Escherichia coli* of the membrane-bound form of human and rat cytochrome b5 and studies on their mechanism of function. *Arch. Biochem. Biophys.* **312**, 554–565
40. Grisshammer, R., Little, J., and Aharony, D. (1994) Expression of rat NK_2 (neurokinin A) receptor in *E. coli*. *Receptors Channels* **2**(4), 295–302
41. Hayashi, M.K. and Haga, T. (1997) Palmitoylation of muscarinic acetylcholine receptor m2 subtypes: Reduction in their ability to activate G proteins by mutation of a putative palmitoylation site, cysteine 457, in the carboxyl-terminal tail. *Arch. Biochem. Biophys.* **340**, 376–382
42. Miller, J.H., Gibson, V.A., and McKinney, M. (1991) Binding of [^{3}H]AF-DX 384 to cloned and native muscarinic receptors. *J. Pharmacol. Exp. Ther.* **259**, 601–607

Downloaded from http://jb.oxfordjournals.org/ at Cold Spring Harbor Laboratory on March 7, 2012