PURIFICATION AND FUNCTIONAL RECONSTITUTION OF MONOMERIC µ-OPIOID RECEPTORS: ALLOSTERIC MODULATION OF AGONIST BINDING BY Gi2

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Running Title: Functional G protein coupling by a µ-opioid receptor monomer

Despite extensive characterization of the µ-opioid receptor (MOR) the biochemical properties of the isolated receptor remain unclear. In light of recent reports we proposed the monomeric form of MOR can activate G proteins and be subject to allosteric regulation. A µ-opioid receptor fused to yellow fluorescent protein (YMOR) was constructed and expressed in insect cells. YMOR binds ligands with high affinity, displays agonist-stimulated [³⁵S]GTPγS binding to Gαi, and is allosterically regulated by coupled G i protein heterotrimer both in insect cell membranes, and as purified protein reconstituted into a phospholipid bilayer in the form of high density lipoprotein (rHDL) particles. Single particle imaging of fluorescently-labeled receptor indicates that the reconstituted YMOR is monomeric. Moreover, single molecule imaging of a Cy3-labeled agonist, [Lys⁷, Cys⁸]dermorphin, illustrate a novel method for studying GPCR-ligand binding and suggests that one molecule of agonist binds per monomeric YMOR. Together these data support the notion that oligomerization of the µ-opioid receptor is not required for agonist and antagonist binding, and that the monomeric receptor is the minimal functional unit in regard to G protein activation and strong allosteric regulation of agonist binding by G proteins.

Opioid receptors are members of the G protein-coupled receptor (GPCR) super-family and are clinical mainstays for inducing analgesia. Three isoforms of opioid receptors, µ, δ and κ, have been cloned and are known to couple to Gi/o proteins to regulate adenylyl cyclase and K⁺/Ca²⁺ ion channels (1-3). An ever growing amount of data suggests that many GPCRs oligomerize (4,5) and several studies have suggested that µ- and δ-opioid receptors (MOR and DOR) heterodimerize to form unique ligand binding and G protein activating units (6-10). While intriguing, these studies utilize cellular over-expression systems where it is difficult to know the exact nature of protein complexes formed between the receptors.

In order to study the function of isolated GPCRs, our laboratory and others have utilized a novel phospholipid bilayer reconstitution method (11-16). In this approach purified GPCRs are reconstituted into the phospholipid bilayer of a high density lipoprotein (HDL) particle. The reconstituted HDL (rHDL) particles are monodispersed, uniform in size, and preferentially incorporate a GPCR monomer (14,15). Previous work in our lab has shown that rhodopsin, a class A GPCR previously proposed to function as a dimer (17-19), is fully capable of activating its G protein when reconstituted as a monomer in the rHDL lipid bilayer (15). Moreover, we have demonstrated that agonist binding to a monomeric β2-adrenergic receptor, another class A GPCR, can be allosterically regulated by G proteins (14). This led us to determine if a monomer of MOR, a class A GPCR which endogenously binds peptide ligands, is the minimal functional unit in regard to G protein activation and strong allosteric regulation of agonist binding by G proteins.

To study the function of monomeric MOR we have purified a modified version of the receptor to near homogeneity. A yellow fluorescent protein was fused to the amino-
terminus of MOR, and this construct (YMOR) was expressed in insect cells for purification. After reconstitution of purified YMOR into rHDL particles, single molecule imaging of Cy3-labeled and Cy5-labeled YMOR determined that the rHDL particles contained one receptor. This monomeric YMOR sample binds ligands with affinities nearly equivalent to those observed in plasma membrane preparations. Monomeric YMOR efficiently stimulates GTPγS binding to G2 heterotrimeric G protein. G2 allosteric regulation of agonist binding to rHDL•YMOR was also observed. Single particle imaging of binding of [Lys7, Cys8]dormorphin-Cy3, a fluorophore-labeled agonist, to rHDL•YMOR supports the notion that the rHDL particles contain a single YMOR. Taken together, these results suggest that a monomeric MOR is the minimal functional unit for ligand binding and G protein activation and illustrate a novel method for imaging ligand binding to opioid receptors.

Experimental Procedures

Materials. G protein baculoviruses encoding rat Gαi2, His8-Gβ1, and Gγ2 were provided by Dr. Alfred G. Gilman (University of Texas Southwestern, Dallas, TX). DNA encoding human µ opioid receptor (NM 000914.2) was provided by Dr. John R. Traynor (University of Michigan, Ann Arbor, MI). Expired serum was generously provided by Dr. Bert La Du (University of Michigan, Ann Arbor, MI). Spodoptera frugiperda (Sf9) and Trichoplusia ni (HighFive TM) cells, pFastBac™ Baculovirus expression vectors and Sf900™ Serum Free Medium were from Invitrogen (Carlsbad, CA). InsectExpress™ medium was purchased from Lonza (Allendale, NJ). N-dodecyl-β-D-maltoside was from Dojindo (Rockville, MD). All lipids were from Avanti Polar Lipids (Alabaster, AL). [3H]diprenorphine (DPN, 54.9 Ci/mmmole) and [35S]GTPγS (1250 Ci/mmmole) were obtained from PerkinElmer (Waltham, MA). EZ-Link™ NHS-Biotin reagent was from Pierce (Rockford, IL). Ovomucoid Trypsin Inhibitor was purchased from United States Biological (Swampscott, MA). GF/B and BA85 filters, Cy3 and Cy5 NHS-ester monoreactive dyes, Cy3-maleimide dye, and Source 15Q and Superdex 200 chromatography resins were from GE Healthcare (Piscataway, NJ). Talon™ resin was from Clontech (Mountain View, CA). Bio-Beads™ SM-2 absorbent resin was from Bio-Rad (Hercules, CA). Chromatography columns were run using a BioLogic Duo-Flow Protein Purification System from Bio-Rad. Amicon Ultra centrifugation filters were from Millipore (Billerica, MA). Amino acids for ligand synthesis were obtained from Advanced ChemTech (Louisville, KY) or Sigma-Aldrich (St. Louis, MO). All other chemicals and ligands were from either Sigma-Aldrich (St. Louis, MO) or Fisher Scientific (Pittsburgh, PA).

YFP-µ-opioid receptor fusion protein expression and purification. Baculoviruses were created using transfer vectors (pFastBac™) that encoded a fusion protein of an N-terminal cleavable hemagglutinin signal sequence (MKTIALS YIFCLVF), a FLAG epitope (DYKDDDD), a deca-histidine tag, the monomeric and enhanced yellow fluorescent protein (Clontech) and the human µ–opioid receptor (MOR). High titer viruses (107 to 108 pfu/mL) were used to infect Sf9 or HighFive™ suspension cultures at a MOI of 0.25 to 1. FLAG-His10-mEYFP-MOR (YMOR) was expressed for 48 to 52 hrs in the presence of 1 µM naltrexone (NTX). Cells were resuspended in Buffer A (50 mM Tris•HCl pH 8.0, 50 mM NaCl, 100 nM NTX and protease inhibitors (3.2 µg/mL leupeptin, 3.2 µg/mL Ovomucoid Trypsin Inhibitor, 17.5 µg/mL phenylmethanesulphonyl fluoride (PMSF), 16 µg/mL tosyl-L-lysine-chloromethyl ketone (TLCK), 16 µg/mL tosyl-L-phenylalanine chloromethyl ketone (TPCK)) and lysed by nitrogen cavitation. Supernatants from a 500 x g spin were then subjected to 125,000 x g spin for 35 min and pellets containing membrane fractions were resuspended in Buffer A and either stored at -80°C for later binding assays or further processed to purify receptor.

All purification steps were performed sequentially and at 4°C or on ice. Membrane preparations were diluted to 5 mg/mL in Buffer A plus 1% DDM (w/v) and 0.01% cholesteryhemisuccinate (CHS) (w/v) and gently stirred for 1 hr to solubilize YMOR out of the membrane. Detergent extracted YMOR was enriched via Talon™ metal affinity chromatography resin (Clontech) in Buffer A plus 0.1% DDM and
0.01% CHS, and eluted with Buffer A plus 0.1% DDM, 0.01% CHS and 150 mM imidazole. Fractions containing YMOR (based on Coomassie staining after SDS-PAGE separation) were pooled, diluted 5-fold in Buffer B (20 mM Hepes pH 8.0, 5 mM MgCl₂, 0.1% DDM, 0.01% CHS, 100 mM NTX, and PMSF-TLCK-TPCK protease inhibitors) and eluted from a 1 mL Source 15Q strong anion-exchange column with a 50-300 mM NaCl linear gradient. Peak fractions were identified by radioligand binding assays using [³H]DPN (2-4 nM). Peak fractions were then pooled and concentrated on Amicon Ultra centrifugation filters (10 kDa MW cut-off). As a final purification step this YMOR sample was resolved based on size using a Superdex 200 gel filtration column (GE Healthcare) in Buffer C (20 mM Hepes pH 8.0, 100 mM NaCl, 0.1% DDM, 0.01% CHS, 100 nM NTX and protease inhibitors). Coomassie staining after SDS-PAGE was used to identify fractions containing YMOR, which were pooled and concentrated to ~1-2 µM.

Glycerol was added to a final concentration of 10% (v/v), samples were flash-frozen in liquid nitrogen and then stored at -80°C until further use.

ApolipoproteinA-1 purification. Wild type human apoA-1 was purified from expired serum as previously described (14). A recombinant apoA-1 with an N-terminal 43 amino acid deletion and a histidine tag (∆(1-43)-His₆-ApoA-1) was expressed using a pET15b vector to transform competent Escherichia coli cells (BL21). Cells were resuspended and lysed by gentle vortexing in 10 mM Tris•HCl pH 8.0, 100 mM NaH₂PO₄, 6 M guanidine hydrochloride (GuHCl), 1% triton X-100. Lysate was fractionated by centrifugation at 10,000 x g and the supernatant was loaded onto a Ni-NTA column by gravity flow. The column was washed with 10 mM Tris•HCl pH 8.0, 100 mM NaCl, 0.1% DDM, 0.01% CHS, 100 nM NTX and protease inhibitors). Coomassie staining after SDS-PAGE was used to identify fractions containing YMOR, which were pooled and concentrated to ~1-2 µM. Glycerol was added to a final concentration of 10% (v/v), samples were flash-frozen in liquid nitrogen and then stored at -80°C until further use.

In vitro HDL reconstitution. HDL particles were reconstituted according to previously reported protocols (14). Briefly, 21 mM Na•cholate, 7 mM lipids (1-palmitoyl-2-oleoyl-sn-glycro-3-phosphocholine (POPC) and 1-palmitoyl-2-oleoyl-sn-glyero-3-[phospho-rac-(1-glycerol)] (POPG) at a molar ratio of 3:2), purified YMOR (DDM-solubilized) and 100 µM purified apoA-1 were solubilized in 20 mM Hepes pH 8.0, 100 mM NaCl, 1 mM EDTA, 50 mM Na•cholate. The final concentration of YMOR varied from 0.2 to 0.4 µM, but YMOR always comprised 20% of the total reconstitution volume. In some reconstitutions the lipid component was modified such that porcine polar brain lipid extract (Avanti Polar Lipids) was used in addition to POPC and POPG for a final concentration of 7 mM lipids at a molar ratio of 1.07:1.5:1 brain lipid:POPC:POPG. Following incubation on ice (1.5 to 2 hr), samples were added to Bio-Beads™ (Bio-Rad, 0.05 mg/mL of reconstitution volume) to remove detergent and to form HDL particles. Particles containing YMOR were purified via M1 anti-FLAG immunaffinity chromatography resin (Sigma), eluted with 1 mM EDTA plus 200 µg/mL FLAG peptide. To assess the efficiency of HDL reconstitution, the total protein concentration of rHDL•YMOR was compared to the concentration of active reconstituted YMOR. FLAG affinity-column purified rHDL•YMOR was resolved from BSA and FLAG peptide on a Superdex 200 gel filtration column and the peak fraction was analyzed for protein content with amido black staining (20), while [³H]DPN saturation assays were used to measure active YMOR content. YMOR reconstituted into HDL was stored on ice until further use.

G protein addition to rHDL•YMOR particles. G₁₂ heterotrimer (Gα₁₂-His₆-Gβ₁-Gγ₂) was expressed in Sf9 cells and purified as previously described (21). The concentration of active G protein was determined by filter binding of 20 µM [³⁵S]GTPγS (isotopically diluted) in 30 mM Na•Hepes pH 8.0, 100 mM NaCl, 50 mM MgCl₂, 1 mM EDTA, 0.05% C₁₂E₁₀, and 1 mM DTT after 1 hr incubation at room temperature. Purified G protein was concentrated to ~10 mg/mL and stored at -80°C until use.
heterotrimer was added to preformed, FLAG-purified rHDL•YMOR particles at a molar ratio of 1:10 receptor to G protein. G_{2} was purified in 0.7% CHAPS, and the final volume of G protein added to rHDL•YMOR was such that the final CHAPS concentration was well below its critical micelle concentration. Reconstituted receptor and G protein samples were then incubated in BioBeads™ for 30-45 min at 4°C to remove residual detergent.

[^3]H]DPN saturation and agonist competition binding assays. Binding reactions were performed in 100 µL volumes. Membrane fractions prepared from Sf9 or HighFive™ cells expressing YMOR (0.5 to 5 µg total protein, prepared as above) were incubated with [^3]H]DPN (0.25 to 4 nM; 54.9 Ci/mmole) for 1 hr at room temperature in 25 mM Tris•HCl pH 7.7, 136 mM NaCl, 2.7 mM KCl (TBS) buffer. Nonspecific binding was determined in the presence of 20 µM NTX. Bound [^3]H]DPN was separated from free by rapid filtration through GF/B filters and three 200 µL washes of ice cold TBS. [^3]H]DPN saturation binding reactions on YMOR incorporated into rHDL particles were prepared in TBS pH 7.7, plus 0.1% BSA, and Sephadex G-50 Fine (GE Healthcare) gravity-flow columns were used to separate bound from free [^3]H]DPN. Agonist competition assays in insect membranes and rHDL particles were performed in 25 mM Tris•HCl pH 7.7, 6-7 mM NaCl. Competition assays in rHDL particles also included 0.1% BSA. [^3]H]DPN binding assays on detergent-solubilized YMOR were performed in 50 mM Tris•HCl pH 7.7, 136 mM NaCl, 0.1% DDM, 0.01% CHS and separated on Sephadex G-50 gravity flow columns. For agonist competition assays receptor samples were incubated with 0.5 to 1 nM [^3]H]DPN and increasing concentrations of agonist (1 pM to 1 mM) in the absence or presence of 10 µM GTPγS. Samples were measured for radioactivity on a liquid scintillation counter and the data were fit with one-site saturation, one-site competition or two-site competition binding models using Prism 5.0 (GraphPad, San Diego, CA).

[^35]S]GTPγS binding assay. One hundred µL volume reactions were prepared containing 1 µg total membrane protein from YMOR expressing HighFive™ cells or ~50-60 fmoles of YMOR incorporated into rHDL particles in 30 mM Tris•HCl pH 7.4, 100 mM NaCl, 5 mM MgCl₂, 0.1 mM DTT, 10 or 1 µM GDP (membranes or HDL particles), and 0.1% BSA. Membrane assays and rHDL assays were incubated with 10 nM isotopically diluted [^35]S]GTPγS (12.5 Ci/mmole). YMOR samples were incubated with increasing concentrations of agonists (1 pM to 1 mM) for 1 hr at room temperature, then rapidly filtered through GF/B (membrane samples) or BA85 filters (HDL samples) and washed three times with 2 mL ice cold 30 mM Tris•HCl pH 7.4, 100 mM NaCl, 5 mM MgCl₂. Samples were measured for radioactivity on a liquid scintillation counter and the data were fit with a log dose-response model using Prism 5.0.

Single molecule imaging of reconstituted Cy3- and Cy5-YMOR. Purified YMOR (~200 picomoles) was incubated with NHS-ester Cy3 or Cy5 mono-reactive dye (GE Healthcare) in 20 mM Hepes pH 8.0, 100 mM NaCl, 5 mM MgCl₂, 6 mM EDTA, 0.1% DDM, 0.01% CHS, 100 nM NTX for 30 min at 25°C and then 1 hr at 4°C. Conjugation reactions were quenched by the addition of Tris•HCl pH 7.7 buffer (10 mM final). Cy-labeled YMOR was then separated from free dye using a 12 cm Sephadex G-50 column. The final dye to protein molar ratio was 3.8:1 for Cy3-YMOR and 3.7:1 for Cy5-YMOR, determined by absorbance at 280 nm for total protein, 550 nm for Cy3 dye, and 650 nm for Cy5 dye as measured on a NanoDrop ND-1000 spectrophotometer. A separate aliquot of YMOR was co-labeled with both Cy3 and Cy5 for final molar ratios of 2:1 Cy3:YMOR and 1.8:1 Cy5:YMOR. HDL reconstitutions of Cy3-YMOR alone, Cy5-YMOR alone, a mixture of Cy3- and Cy5-YMOR, and Cy3-Cy5-YMOR were then performed. Reconstitutions were performed as previously described, using apoA-1 which had been biotinylated at a 4:1 molar ratio using EZ-Link NHS-Biotin according to the manufacturer’s protocol (Pierce). Reconstituted samples were diluted 5000-fold in 25 mM Tris•HCl, pH 7.7 and injected into a microfluidic channel on a quartz slide which was previously coated with biotinylated-PEG and treated with 0.2 mg/mL streptavidin to generate a surface density of ~0.05 molecules per µm². An oxygen scavenging system by guest on August 17, 2017 http://www.jbc.org/ Downloaded from
(OSS) of 10 mM trolox, 100 mM protocatechuic acid (PCA) and 1 µM protocatechuate-3,4-dioxygenase (PCD) was included in the sample dilution (22). Following a 10 min incubation to allow binding of the biotin-HDL•Cy-YMOR complex to the streptavidin coated slide, the channel was washed with ice cold 25 mM Tris•HCl pH 7.7 containing the OSS. An Olympus IX71 inverted microscope configured for prism-based total internal reflection fluorescence (TIRF) and coupled to an intensified CCD camera was used to image Cy3 and Cy5 fluorophores (CrystaLaser - 532 nm, Coherent CUBE laser - 638 nm, Chroma bandpass filters HQ580/60 and HQ710/130 nm). Fluorophore intensity time traces were collected for 30 to 100 s at 10 frames per s. Time traces were analyzed for photobleaching with in-house software (MatLab 7.0).

Synthesis of [Lys7, Cys8]dermorphin and labeling with Cy3 dye. [Lys7, Cys8]dermorphin (Tyr-D-Ala-Phe-Gly-Tyr-Pro-Lys-Cys-NH2) was synthesized on Rink resin (solid support) using an Applied Biosystems 431A Peptide Synthesizer and standard Fmoc chemistry. Samples were characterized on a Waters reverse phase HPLC using a Vydac C18 (Protein and Peptide) 10 micron column. Samples were run on a linear gradient of 0 to 45% acetonitrile in an aqueous phase containing 0.1% TFA at 35°C, and monitored at 254 and 230 nm (Supplemental Figure 2). Peptides were similarly purified on a Waters semi-preparative RP-HPLC using a Vydac C18 10 micron column at room temperature. The purified peptide was labeled with Cy3-maleimide (GE Healthcare) according to the manufacturer’s instructions using a ratio of 1:5:1 peptide to fluorophore and repurified by HPLC as before. The labeled peptide was further purified via semi-preparative HPLC using a 5 micron Vydac C18 column as described above. The potency and efficacy of [Lys7, Cys8]dermorphin-Cy3 at MOR were confirmed in radiolabeled [3H]DPN competition and [35S]GTPγS binding assays.

Prism-based Single Molecule TIRF and Step-Photobleaching analysis of [Lys7, Cys8]dermorphin-Cy3 binding to rHDL•YMOR+Gi2. Purified recombinant apoA-1 was biotinylated at a 3:1 molar ratio of biotin:apoA-1. Purified YMOR was then reconstituted with biotin-apoA-1, POPC, POPG, and brain lipid extract as above. Purified Gi heterotrimer was added to reconstituted receptor as above, and coupling was confirmed by observing high affinity competition of [3H]DPN binding by the agonist DAMGO. Five nanomolar biotin-rHDL•YMOR+Gi2 was then incubated with 5 µM [Lys7, Cys8]dermorphin-Cy3 for 45 min at 25°C in 25 mM Tris•HCl pH 7.7. Samples were diluted 100-fold in 25 mM Tris•HCl pH 7.7 and imaged as described above with a surface density of ~0.25 molecules per µm². Fluorophore intensity time-traces were collected for 30 to 100 s at 10 frames per s and analyzed for photobleaching with in-house software (MatLab 7.0).

Results

Expression of a functional µ-opioid receptor fusion protein in insect cells. Yellow fluorescent protein-tagged human MOR (YMOR, Figure 1a) expressed in Sf9 and HighFive™ insect cells bound the non-specific opioid antagonist [3H]diprenorphine ([3H]DPN) with high affinity in a saturable manner (Kd = 0.6 ± 0.1 nM; Figure 1b). Maximal receptor levels of 12 to 40 pmol/mg were routinely observed.

The µ-selective agonist DAMGO ([D-Ala², N-MePhe⁴, Gly⁵-ol]enkephalin) stimulated [35S]GTPγS binding to membranes co-expressing YMOR and Gαi2-His6Gβ1-Gγ2 G protein heterotrimer (G i2) in a concentration dependent manner (Figure 1c). DAMGO elicited strong activation of G i2, stimulating [35S]GTPγS binding nearly four-fold over basal levels with an EC50 of 36 ± 0.1 nM. The potency and efficacy of DAMGO at insect cell expressed YMOR is well in line with its observed pharmacological characteristics in mammalian cell expression systems (23-25).

Allosteric regulation of agonist binding to opioid receptors by G proteins has been well established in plasma membrane preparations of brain homogenates and over-expression systems (26-30) and was also observed for YMOR expressed in insect cells. In the absence of G i2, DAMGO competed [3H]DPN (0.5 nM) binding in a concentration-dependent manner with a Kd of ~576 nM (Figure 1d). In membranes expressing both YMOR and Gi2, DAMGO exhibited a
biphasic mode of inhibition of [3H]DPN binding with Ki hi ~2.9 nM and Ki lo ~1.5 μM (fraction of Ki hi ~0.53). The addition of 10 μM GTPγS to the YMOR + Gi2 membranes eliminated the high affinity DAMGO binding site (Ki ~300 nM), illustrating that YMOR is allosterically regulated by G proteins. Therefore YMOR expressed in HighFive™ cells proved fully functional in regards to G protein coupling.

YMOR purification. The capacity of a variety of detergents (zwitterionic, polar and non-ionic detergents such as Triton X-100, digitonin, NP40, CHAPS, C12E10 and n-octyl-β-glucoside) to solubilize YMOR from insect cell membranes was assessed by anti-FLAG western blot analysis. Extraction of YMOR with n-dodecyl-β-D-maltoside (DDM) proved to be most efficient (data not shown). The addition of cholesteryl hemisuccinate (CHS, 0.01% w/v) improved the stability of the solubilized receptor as measured by [3H]DPN binding, consistent with the stabilizing effects of cholesterol moieties observed for solubilized β2AR (31) (Supplemental Figure 1). The expression levels of YMOR and the efficiency of DDM solubilization, assessed by [3H]DPN binding and anti-FLAG western blots, were enhanced in the presence of naltrexone. Therefore this antagonist was present (100 nM) during all subsequent purification steps.

DDM-extracted YMOR was purified through a series of chromatographic steps including metal chelate (Talon™), anion exchange (Source 15Q) and size exclusion (Superdex 200) chromatography columns. Peak fractions from each column were determined by Coomassie staining, anti-FLAG antibody western blotting and [3H]DPN binding. Fractions displaying the highest [3H]DPN binding capacity and appropriate molecular weight were pooled and subjected to the next chromatographic step. Superdex 200 peak fractions were pooled, concentrated and flash-frozen in liquid N2, then stored at -80°C until later use. A representative silver-stained SDS-PAGE separation of each enrichment step is shown in Figure 2a. Yields of YMOR were typically ~50 μg of >95% pure receptor per liter of insect culture. YMOR, deemed pure based on silver staining, bound [3H]DPN at approximately 20% of the predicted binding sites calculated from the molecular mass. This loss of activity is likely due to the detrimental freeze/thaw process.

Reconstitution of YMOR into High Density Lipoprotein particles. The reconstitution of YMOR into high density lipoprotein (rHDL) particles was performed with a 500-fold molar excess of apoA-1 to YMOR (250-fold excess of rHDL) to favor reconstitution of a single YMOR molecule per rHDL particle. Resolution of rHDL particles containing YMOR (rHDL•YMOR) with size exclusion chromatography (SEC) suggested an apparent Stokes diameter of 10.5 nm (Figure 2b). [3H]DPN binding to the SEC fractions confirmed the presence of functional YMOR in particles that eluted slightly earlier than the main UV absorbance peak (Stokes diameter of ~10.3 nm), indicating the slightly larger size of rHDL•YMOR compared to rHDL. The YFP fluorescence of the SEC fractions indicated an additional peak that elutes near in the Superdex 200 void volume, suggestive of aggregated YMOR. Since these fractions did not bind [3H]DPN, we surmised that this receptor population was inactive. This aggregated and inactive receptor is consistent with the previous observation that ~80% of the purified YMOR is inactive post freeze/thaw and prior to reconstitution into HDL.

The effectiveness of YMOR reconstitution into HDL is clear when comparing [3H]DPN binding between detergent-solubilized receptor and rHDL•YMOR particles. Prior to reconstitution into HDL, DDM-soluble YMOR bound [3H]DPN with a KD ~4.1 nM whereas reconstituted YMOR bound [3H]DPN with a KD of ~0.4 nM (Figure 2c). This significant disruption of high affinity ligand binding for the soluble receptor is not surprising, as detergents are known to decrease ligand affinity of opioid receptors (32), and disrupt GPCRs in general (33). Replacement of detergents with phospholipids reverses the detergent’s deleterious effects and restores YMOR’s conformation to one that binds [3H]DPN with native, membrane-bound affinity.

YMOR is monomeric when incorporated into rHDL. In order to determine the number of YMOR molecules present in each rHDL particle, we assessed the degree of receptor co-localization between Cy3- and Cy5-labeled YMOR using...
single particle imaging. Purified YMOR was labeled with Cy3- or Cy5-reactive fluorescent dyes and reconstituted into HDL using biotinylated Δ(1-43)-His6-apoA-1. This biotin-rHDL•Cy-YMOR complex was then incubated on a streptavidin-coated microfluidic slide and excited with 532 and 638 nm lasers. Fluorescence emission was detected using prism-based single molecule total internal reflection fluorescence (SM-TIRF). Reconstituted Cy3-YMOR and Cy5-YMOR were visualized as mono-disperse fluorescent foci (Figure 3a and b). When Cy3-YMOR and Cy5-YMOR were mixed prior to reconstitution (Cy3-YMOR+Cy5-YMOR), a low level of co-localization of the two fluorophores (3.4%) was observed (Figure 3c and e). A false-positive co-localization signal of 2.8% and 2.2% was observed for the Cy3-YMOR and Cy5-YMOR samples, respectively (Figure 3e). As a positive control, co-localization for YMOR labeled with both Cy3 and Cy5 was also measured (Figure 3d). Considering that our method does not allow for the differentiation between YMOR labeled with multiple Cy probes of the same fluorophore versus co-localization of multiple YMORs labeled with the same Cy probe, we may underestimate co-localization by as much as a factor of 2. Thus we estimate an upper limit for co-localization, i.e. incorporation of two or more YMORs into a single rHDL particle, of ~1.8% ((3.4% x 2) - (2.8% + 2.2%)). These results suggest that HDL reconstitution resulted in a sample containing mostly monomeric YMOR. Therefore the ligand binding and G protein coupling characteristics of the HDL reconstituted YMOR presented here are indicative of the properties of a monomeric receptor.

In order to assess the amount of active versus inactive YMOR incorporated into rHDL, we compared the total protein concentration of purified rHDL•YMOR particles to the maximal concentration of YMOR based on [3H]DPN saturation binding assays. Reconstituted YMOR was purified using FLAG-affinity resin and resolved by SEC into a sample containing only apoA-1 and YMOR (based on SDS-PAGE and Coomassie staining). Amido black staining of these peak fractions indicated a protein concentration of ~5.2 µg/mL. Considering the protein sample consists of two apoA-1 molecules (MW ~25500 Da) and one YMOR (MW ~73500 Da), the rHDL•YMOR sample has a total MW of 124500 Da, and a molar concentration of ~42 nM. Saturation binding assays on the rHDL•YMOR SEC peak indicated a molar concentration of ~31 nM for YMOR which bound ligand. Given the inherent limitations of protein detection assays at the low concentration of our samples, these data suggest that at least 75% of the YMOR in rHDL is active based on [3H]DPN binding.

**Monomeric YMOR binds antagonists with high affinity.** Reconstituted and monomeric YMOR binds antagonists with affinities similar to those observed in the plasma membrane. The antagonists naloxone and naltrexone, and the µ-specific peptide CTAP (D-Phe-Cys-Tyr-D-Trp-Arg-Thr-Pen-Thr-NH2) compete [3H]DPN binding in similar fashion when in HighFive™ cell membrane preparations or in reconstituted HDL particles (Figure 4a). Therefore reconstitution into HDL allows YMOR to adopt a conformation that appears identical to receptor in plasma membranes in terms of high affinity antagonist binding.

**Monomeric YMOR functionally couples inhibitory G proteins.** We next analyzed the capacity of monomeric YMOR to functionally couple to heterotrimeric G protein. Functional measurements included allosteric regulation of agonist binding (Figure 4b) and agonist mediated stimulation of [35S]GTPγS binding (Figure 4c). Anti-FLAG column-purification of rHDL•YMOR was performed to remove “empty” rHDL particles and purified G12 heterotrimer was added at a 10:1 G12:rHDL•YMOR molar ratio. The concentration of purified G protein was determined by [35S]GTPγS binding assays and receptor concentration was measured with [3H]DPN saturation assays of rHDL•YMOR samples. G12 addition results in high affinity agonist binding (Figure 4b). Morphine competed [3H]DPN binding with a Ki hi of ~1.6 nM and a Ki lo of ~320 nM while DAMGO inhibited with a Ki hi ~7.6 nM and a Ki lo ~1.8 µM. As in membranes the addition of 10 µM GTPγS to the monomeric rHDL•YMOR+G12 uncouples the G protein and results in a single site, low affinity agonist competition curve. Similarly, when rHDL•YMOR was not coupled to G12, DAMGO competed...
[3H]DPN binding with micromolar affinity (Supplemental Figure 2).

Just as YMOR membrane preparations displayed DAMGO-induced [35S]GTPγS binding to G_{i2}, monomeric YMOR in rHDL particles showed strong DAMGO stimulation of nucleotide exchange (~4.7-fold stimulation with an EC_{50} of 31 ± 2.2 nM, Figure 4c). A fluorescently-labeled agonist, [Lys^7, Cys^8]dermorphin-Cy3 was also tested and showed concentration-dependent stimulation of [35S]GTPγS binding to G_{i2} by monomeric YMOR (EC_{50} of 32 ± 9.1 nM, Supplemental Figure 4b).

Although G_{i2} was added to rHDL•YMOR at a 10:1 molar ratio in these reconstitutions, the observed high and low agonist affinities illustrate that not all YMOR was coupled to G_{i2}. In fact, the agonist competition assays indicate that approximately 54% of the receptor was coupled to G_{i2}. These data are consistent with previous studies on the β_{2}AR where the addition of purified G protein heterotrimer to rHDL particles in the absence of detergents resulted in 90-95% G protein loss, due largely to aggregation (14). Indeed, SEC analysis of rHDL•YMOR before and after G_{i2} addition confirmed that a large amount of the heterotrimer aggregates during its addition (data not shown). As such, the two populations of ~54% coupled and ~46% uncoupled YMOR correspond well within the expected final G protein to YMOR ratio of 0.5-1:1.

**Discussion**

Intense research over the past decade has focused on the existence and functional consequences of GPCR oligomerization. Recently, our laboratory and others have taken advantage of a unique phospholipid lipid bilayer platform in the form of reconstituted high density lipoprotein (rHDL) particles (13-16). Using this system we previously demonstrated the functional reconstitution of two prototypical GPCRs, rhodopsin and β_{2}AR (14,15). Having illustrated that these receptors are monomeric following reconstitution, we observed complete functional coupling to their respective G proteins. For the β_{2}AR, agonist binding to monomeric receptor is allosterically regulated by the stimulatory heterotrimeric G protein G_{α}βγ. Therefore GPCR dimerization is not required for functional G protein coupling in the prototypical class A GPCRs rhodopsin and β_{2}AR.

In contrast, the accumulation of considerable biochemical and biophysical evidence suggests that the μ, δ, and κ opioid receptors may function in a fashion that is dependent on their oligomerization. Analysis of receptor over-expression in co-transfected cells suggested the existence of δ-δ homodimers (34) and demonstrated unique pharmacology resulting from μ-δ (6,7,10) and δ-κ heterodimers (35). Bioluminescence resonance energy transfer (BRET) studies have shown that homo- and heterodimers can be formed by all three opioid receptor isoforms (8). These findings have promoted the notion that opioid receptor oligomerization is important for function (36,37). However with co-transfection systems the final
profile of $\mu$ and $\delta$ monomers, homo- and heterodimers is unknown. In light of these reports, we rationalized that it was vital to determine whether the monomeric form of the $\mu$-opioid receptor (MOR) behaves in a pharmacologically similar manner as the native, membrane-bound form.

The HDL reconstitution system was used to investigate the function of monomeric MOR. Reconstitution of MOR required the purification of active receptor in large enough quantities for subsequent biochemical manipulation and analysis. Previous reports of MOR purification from endogenous or recombinant sources have yielded either low quantities (38-42) or poor agonist binding affinities (43-45). Several aspects were key to the expression and purification of YFP-MOR (YMOR): a cleavable hemagglutinin signal sequence at the receptor’s N-terminus (46), the presence of naltrexone during expression, and the inclusion of cholesteryl hemisuccinate and naltrexone during the entire purification process. These modifications contributed to the stabilization of YMOR, leading to an increase in yields during the chromatography process as well as increasing the specific activity of the detergent solubilized receptor. Reconstitution into HDL facilitated the isolation of a monomeric form of YMOR that couples to and activates heterotrimeric G proteins. Furthermore, we illustrate that the inhibitory G protein $G_{i\alpha}G_{b\gamma}$ can allosterically regulate agonist binding to monomeric MOR. These results suggest that G protein regulation of monomeric receptors is likely a phenomenon common to all G proteins and class A GPCRs. The capacity of MOR to couple to various isoforms of $G_{i\alpha}$ heterotrimers in a differential manner are currently under investigation in our laboratory.

Taken together we demonstrated the functionality of monomeric MOR, illustrating that the opioid GPCR does not require dimerization to bind ligands and signal to G proteins. However, these data do not refute the existence of opioid receptor oligomerization in cells. It remains possible that homo- and heterodimerization creates unique ligand binding entities that may be subject to differential regulation, desensitization, and internalization. One of our future goals is to isolate various oligomeric states of opioid receptors and other GPCRs in rHDL particles, and compare their activities towards ligands and signaling partners directly. A major technical obstacle is the formation of ‘anti-parallel’ receptor dimers, where the amino termini for the reconstituted GPCRs in the oligomer are on opposite sides of the phospholipid bilayer. Indeed, reconstitution of two GPCRs in a single rHDL particle has been previously demonstrated for rhodopsin (13,16), but a detailed analysis by nano-gold labeling and single particle electron microscopy of the reconstituted ‘dimers’ reveals that a significant fraction were anti-parallel (16). It is plausible, and even likely, that an anti-parallel GPCR dimer will result in suboptimal or disrupted G protein coupling. The development of approaches to insure parallel GPCR dimer incorporation into rHDL particles to confidently study the functional relevance of opioid receptor dimerization are currently a major priority in the laboratory.

HDL reconstitution of YMOR also provided a platform for analysis of ligand binding using single molecule microscopy. In this study we examined the reversible binding of a $\mu$-opioid receptor specific agonist $[\text{Lys}^7, \text{Cys}^8]\text{dermorphin}$ (47) with SM-TIRF. To the best of our knowledge these data represent the first reported observation of a peptide agonist binding to an isolated GPCR in a lipid bilayer using single particle imaging. We are currently refining our methods to resolve the kinetics of ligand binding to YMOR, as well as visualizing ligand binding to opioid receptors in intact cells. Peptide receptors such as the opioid family are particularly amenable to fluorescence spectroscopy since the relatively large ligand size can tolerate the incorporation of fluorophores without drastically impairing binding affinities. This single molecule visual approach of studying ligand binding to opioid receptors, utilizing labeled agonists and antagonists with unique binding affinities towards receptor homo- and heterodimers, may potentially address opioid receptor oligomerization in physiologically relevant tissue preparations.

Acknowledgements
The authors thank Drs. John Traynor and Richard Neubig for critical discussion of this work. This research was made possible by grant numbers GM068603 (R.K.S.), GM07767 (A.J.K. and J.P.A.) and GM081025 (S.P. and N.G.W.) from NIGMS. Additional funding was provided by a Pilot and Feasibility Grant from the Michigan Diabetes Research and Training Center, NIH/NIDDK Grant P60-DK020572 (R.K.S.).

**Abbreviations**

MOR, µ-opioid receptor; YMOR, yellow fluorescent protein tagged MOR; GPCR, G protein-coupled receptor; G protein, guanosine triphosphate-binding protein; HDL, high density lipoprotein; rHDL, reconstituted HDL particles; apoA-1, apolipoproteinA-1; DPN, diprenorphine; DAMGO, [D-Ala², N-MePhe⁵, Gly⁵-ol]enkephalin; GTPγS, guanosine-5'-(γ-thio)triphosphate; NTX, naltrexone; DDM, N-dodecyl-β-D-maltoside; CHS, cholesteryl hemisuccinate; POPC, 1-palmitoyl-2-oleoyl-sn-glycero-3-phosphocholine; POPG, 1-palmitoyl-2-oleoyl-sn-glycero-3-[phospho-rac-(1-glycerol)]; SDS-PAGE, sodium dodecyl sulfate polyacrylamide gel electrophoresis; BSA, bovine serum albumin; SM-TIRF, single molecule total internal reflection fluorescence.

**References**


Figure Legends

**Figure 1.** Functional expression of a modified MOR in insect cells. (A) Schematic representation of the modified µ-opioid receptor expressed in insect cells. N-terminal modifications included a hemagglutinin signal sequence (HA), FLAG epitope, deca-histidine (His10) and a Yellow Fluorescent Protein (YFP).
This construct, termed YMOR, was expressed in Sf9 and High-Five insect cells using a recombinant Baculovirus system. (B) YMOR expressed in insect cells exhibits high affinity ligand binding. Plasma membrane preparations (5 µg) of HighFive™ cells expressing YMOR were used in [3H]diprenorphine saturation binding assays. YMOR bound [3H]DPN with a B_max of approximately 40 pmol/mg and a K_d of 0.6 ± 0.1 nM. (C) YMOR couples to G protein in insect cell membranes. Membrane preparations (2 µg) of HighFive™ cells co-expressing YMOR and G_i2 heterotrimer were incubated with increasing concentrations of the μ-opioid agonist DAMGO in the presence of 0.1 nM [35S]GTP\gammaS (isotopically diluted). DAMGO stimulated [35S]GTP\gammaS exchange on G_i2 with an EC_{50} of 36 ± 0.1 nM. (D) Agonist binding to YMOR expressed in insect cells is allosterically regulated by G proteins. YMOR/G_i2 membrane preparations (2-3 µg) were incubated with 0.8 nM [3H]DPN and increasing concentrations of DAMGO in the absence or presence of 10 µM GTP\gammaS. A high affinity binding site for DAMGO (●, K_i ~2.9 nM) was disrupted in the absence of G protein coupling (+GTP\gammaS: ■, K_i ~1.5 µM). DAMGO also displayed low affinity when bound to membranes not expressing G_i2 (YMOR: ▲, K_i ~580 nM and YMOR+GTP\gammaS: ▼, K_i ~800 nM). Binding data was normalized to the curve fit maximum. For all panels the data are representative of at least two experiments performed in duplicate and error bars represent the Standard Error of the Mean.

**Figure 2.** Purification of YMOR from HighFive™ insect cells and reconstitution into HDL particles. (A) YMOR was extracted from membranes in the presence of 100 nM naltrexone with 1% n-dodecyl-β-D-maltoside and 0.01% cholesteryl hemi succinate and enriched on a Talon™ metal affinity column. The Talon pool containing YMOR (predicted 73 kDa MW) was applied to a Source 15Q anion exchange column followed by a size exclusion gel filtration column (Superdex 200). Samples of the purification steps were resolved by SDS-PAGE and silver stained. YMOR was enriched to ~95% purity (GF peak). (B) Purified YMOR was reconstituted into HDL particles (see Methods) and resolved by size exclusion chromatography (Superdex 200). Fractions were analyzed for total protein content (UV absorbance), active YMOR ([3H]DPN binding), and YFP fluorescence. UV absorbance showed a major peak corresponding to rHDL particles (stokes diameter of approximately 10.5 nm). Elution volume of active YMOR corresponded with the rising slope of the rHDL peak. YFP fluorescence eluted as two peaks, corresponding to the active YMOR and a larger YMOR aggregate which was not incorporated into rHDL particles. This aggregated YMOR was not active based on [3H]DPN binding. Data was normalized such that the maximal value for each parameter was set to 100%. [3H]DPN binding measurements were performed in duplicate and error bars are omitted for clarity. (C) High affinity [3H]DPN binding to YMOR is disrupted in detergent micelles but restored following reconstitution into rHDL particles. [3H]DPN binding to YMOR in insect cell membranes (●, K_d of ~0.5 nM), purified in DDM micelles (■, K_d of ~4.1 nM), and in rHDL particles (▲, K_d ~0.4 nM). Data are representative of at least three experiments performed in duplicate and error bars represent the Standard Error of the Mean. Binding data was normalized to the maximal binding level (B_max) as calculated by a one-site saturation curve fit (Prism 5.0, GraphPad).

**Figure 3.** YMOR is monomeric when reconstituted into HDL particles. Purified YMOR was labeled with Cy3 or Cy5 fluorescent dyes and reconstituted separately or together into biotin-labeled rHDL. Particles were imaged using single molecule total internal reflection fluorescence microscopy on quartz slides coated with streptavidin. Representative overlay images of reconstituted rHDL•Cy3-YMOR (A), rHDL•Cy5-YMOR (B), rHDL•(Cy3-YMOR + Cy5-YMOR) (C), and rHDL•Cy3-Cy5-YMOR (D) are shown. Quantification of Cy3 and Cy5 colocalization (E) showed that when both Cy3-YMOR and Cy5-YMOR were mixed together prior to reconstitution (mixture, 4c), only approximately 3.4% of rHDL particles contained two labeled receptors, compared to a false-positive co-localization signal of 2.8% and 2.2% observed for the rHDL•Cy3-YMOR and rHDL•Cy5-YMOR samples. YMOR co-labeled with both Cy3 and Cy5 was also imaged as a positive control for co-localization. Approximately 24% of
rHDL•Cy3-Cy5-YMOR particles (co-labeled, 4d) exhibited co-localization, indicating that not all YMOR received a secondary fluorescent dye under the labeling conditions.

**Figure 4.** Monomeric YMOR binds ligands with high affinity and functionally couples to G\textsubscript{i2} heterotrimer. (A) Opioid antagonists bind YMOR in rHDL with affinities equivalent to those observed in membrane preparations. Competition binding assays were performed using plasma membranes of High-Five cells expressing YMOR and G\textsubscript{i2} heterotrimer (dotted lines, open symbols) or rHDL•YMOR (solid lines, closed symbols). For CTAP binding assays in rHDL, YMOR was coupled to G\textsubscript{i2} heterotrimer. Increasing concentrations of naloxone, naltrexone, or CTAP competed the binding of 1 nM [\textsuperscript{3}H]DPN in the rHDL system or 0.5 nM [\textsuperscript{3}H]DPN in membrane preparations. Observed binding constants were: naloxone K\textsubscript{imem} \sim 19 nM, K\textsubscript{irHDL} \sim 7.8 nM; naltrexone K\textsubscript{imem} \sim 4.3 nM, K\textsubscript{irHDL} \sim 3.3 nM; CTAP K\textsubscript{imem} \sim 7.1 nM, K\textsubscript{irHDL} \sim 7.6 nM. (B) Binding of morphine to rHDL•YMOR is allosterically regulated by G proteins. Purified G\textsubscript{i2} heterotrimer was added to rHDL•YMOR at a molar ratio of 10:1, G protein to receptor. DAMGO and morphine bound rHDL•YMOR with high affinity, competing the binding of 0.75 nM [\textsuperscript{3}H]DPN in a biphasic manner (DAMGO (■): K\textsubscript{ih} \sim 7.6 nM, K\textsubscript{il} \sim 1.8 µM; morphine (●): K\textsubscript{ih} \sim 1.7 nM, K\textsubscript{il} \sim 320 nM). High affinity morphine binding was lost with the addition of 10 µM GTP\textsubscript{γS} (DAMGO (□) K\textsubscript{GTP\textsubscript{γS}} \sim 1 µM; morphine (○) K\textsubscript{GTP\textsubscript{γS}} \sim 1 µM). In both A and B, data was normalized to the maximal binding level as calculated by a one- or two-site competition curve fit (Prism 5.0, GraphPad). (C) HDL reconstituted YMOR activates G\textsubscript{i2} in response to agonist binding. YMOR (an estimated 50-60 fmoles) and associated G\textsubscript{i2} heterotrimer were incubated with 10 nM [\textsuperscript{35}S]GTP\textsubscript{γS} (isotopically diluted) in the presence of increasing concentrations of DAMGO. DAMGO activated G\textsubscript{i2} with an EC\textsubscript{50} of 29 ± 1.4 nM, stimulating approximately 40 fmoles of [\textsuperscript{35}S]GTP\textsubscript{γS} binding to G\textsubscript{αi2} over basal levels, suggesting approximately a 1:0.7 coupling between YMOR and G protein. These results correlate with the estimated 53% high state observed in panel B. Data are representative of three experiments performed in duplicate. Error bars represent the Standard Error of the Mean.

**Figure 5.** Single molecule imaging of Cy3-labeled agonist binding to rHDL•YMOR+G\textsubscript{i2} confirms that the majority of YMOR is monomeric when reconstituted into HDL. Binding of [Lys\textsuperscript{7}, Cys\textsuperscript{8}]dermorphin-Cy3, a fluorescently-labeled MOR-specific agonist, to rHDL•YMOR+G\textsubscript{i2} was observed with prism-based total internal reflection fluorescence microscopy. YMOR was reconstituted into HDL particles using biotinylated apoA-1, followed by G\textsubscript{i2} heterotrimer addition at a 30:1 G protein to receptor molar ratio. Reconstituted HDL (A) or rHDL•YMOR+G\textsubscript{i2} (B) were then incubated with a saturating concentration (500 nM) of [Lys\textsuperscript{7}, Cys\textsuperscript{8}]dermorphin-Cy3, adhered to a streptavidin-coated quartz slide and washed with ice-cold 25 mM Tris•HCl pH 7.7 buffer. Bound [Lys\textsuperscript{7}, Cys\textsuperscript{8}]dermorphin-Cy3 was continuously excited at 532 nm to observe photobleaching of the fluorophore. (C) Representative fluorescence intensity traces for a one- and two-step photobleach event are shown. Arrows indicate a photobleach event. (D and E) Quantification of photobleaching showed that approximately 95% of the bound [Lys\textsuperscript{7}, Cys\textsuperscript{8}]dermorphin-Cy3 bleached in a single step, suggesting that 95% of rHDL particles contained monomeric YMOR. [Lys\textsuperscript{7}, Cys\textsuperscript{8}]dermorphin-Cy3 binding was reversible, as shown the addition of 5 µM naltrexone (NTX). A minimum of four slide regions and 200 fluorescent spots were counted for each sample.
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Figure 1

A

YFP

HA|FLAG|His\textsubscript{10}

MOR

B

$[^3H]DPN$ bound (pmol/mg)

$[^3H]DPN$ (nM)

C

$[^35S]GTP\gamma S$ bound (pmol/mg)

\log [DAMGO] (M)

D

$[^3H]DPN$ bound (normalized, % maximal)

\log [DAMGO] (M)

YMOR$+G_i$

YMOR$+G_i + GTP\gamma S$
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Figure 2

A

B

C

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Figure 2

A

B

C
Figure 3

A  B  C

D

E

% of Molecules Co-localized

Gy3  Gy5  mixture  co-labeled

% of Molecules Co-localized
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Figure 4

A

\[ \text{[H]DPN bound (normalized, \%)} \]

\( \log [\text{antagonist}] (\text{M}) \)

-10 -9 -8 -7 -6 -5

-12 -11 -10 -9 -8 -7 -6 -5 -4 -3

B

\[ \text{[H]DPN bound (\%, normalized)} \]

\( \log [\text{agonist}] (\text{M}) \)

C

\[ \text{[35S]GTPγS bound (fmol)} \]

\( \log [\text{DAMGO}] (\text{M}) \)
Purification and functional reconstitution of monomeric mu-opioid receptors: Allosteric modulation of agonist binding by G \textalpha{}2
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\textit{J. Biol. Chem. published online June 19, 2009}

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