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# Reversible, allosteric, small-molecule inhibitors of RGS proteins

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List of Abbreviations:

TR-FRET: Time-Resolved Fluorescence Resonance Energy Transfer

RGS: Regulator of G Protein Signaling

FCPIA: Flow Cytometry Protein Interaction Assay

SMPPII: Small Molecule Protein-Protein Interaction Inhibitor

PPI: Protein-Protein interaction

GAP: GTPase Accelerating Protein

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**Abstract:**

Regulators of G protein Signaling (RGS) proteins are potent negative modulators of G protein signaling and have been proposed as potential targets for small molecule inhibitor development. We report a high throughput time-resolved fluorescence resonance energy transfer (TR-FRET) screen to identify inhibitors of RGS4 and describe the first reversible, small-molecule inhibitors of an RGS protein. Two closely-related compounds, typified by CCG-63802, inhibit the interaction between RGS4 and  $G\alpha_o$  with an  $IC_{50}$  value in the low micromolar range. They show selectivity among RGS proteins with a potency order of RGS 4>19=16>8>>7. The compounds inhibit the GTPase Accelerating Protein activity of RGS4 and thermal stability studies demonstrate binding to the RGS but not to  $G\alpha_o$ . On RGS4, they depend on an interaction with one or more cysteines in a pocket that has previously been identified as an allosteric site for RGS regulation by acidic phospholipids. Unlike previous small molecule RGS inhibitors identified to date, these compounds retain substantial activity under reducing conditions and are fully reversible on the ten minute time scale. CCG-63802 and related analogs represent a useful step towards the development of chemical tools for the study of RGS physiology.

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## Introduction:

Networks of protein-protein interactions are crucial for efficient cellular function. There has been significant interest in developing small molecule inhibitors of specific protein-protein interactions (SMPPPIs) for use as research probes and potential therapeutic agents (Arkin and Wells, 2004; Berg, 2003; Berg, 2008; Blazer and Neubig, 2008; Gadek and Nicholas, 2003). The development of SMPPPIs has been difficult. One challenge has been the lack of clearly identifiable small molecule binding sites on the relatively featureless protein-protein interaction interface. A promising approach is the use of allosteric pockets on the protein target to bypass this problem and, increasingly, there has been solid progress in SMPPPI development (Arkin and Wells, 2004; Arkin and Whitty, 2009; Berg, 2003; Berg, 2008; Blazer and Neubig, 2008; Busschots et al., 2009; Niu and Chen, 2009).

RGS proteins are GTPase accelerating proteins (GAPs) for heterotrimeric G protein  $\alpha$  subunits (Berman et al., 1996). They increase the intrinsic rate of GTP hydrolysis by the  $G\alpha$ , thus reconciling the paradox of the sub-second regulation of G protein signaling *in vivo* vs. the relatively long half life of GTP bound to purified  $G\alpha$  *in vitro*. In mammals, there are over 20 known RGS proteins that interact with limited selectivity to most  $G\alpha$  subtypes (Hollinger and Hepler, 2002; Neubig and Siderovski, 2002).

There is substantial interest in the therapeutic potential of small molecule modulators of RGS proteins (Blazer and Neubig, 2008; Neubig and Siderovski, 2002; Riddle et al., 2005; Traynor et al., 2009; Zhong and Neubig, 2001). In brief, RGS inhibitors may potentiate signaling through GPCRs in a tissue-specific manner due to the localized expression patterns of many RGS

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proteins. This effect could be used to reduce side effects of clinically used GPCR agonists that stem from non-target tissue receptor activation (e.g.  $\mu$ -opioid receptor dependent constipation during post-operative analgesia (Bueno and Fioramonti, 1988)).

To understand the physiological ramifications of inhibiting RGS protein GAP activity, our laboratory has developed two lines of mice that express mutant  $G\alpha_o$  or  $G\alpha_{i2}$  that are insensitive to RGS effects (G184S). These mice show dramatic phenotypes, including resistance to diet-induced obesity and antidepressant-like behavioral effects ((Huang et al., 2008; Huang et al., 2006), and Talbot et al submitted). RGS4 is upregulated in the dorsal horn of spinal cord during the development of neuropathic pain (Garnier et al., 2003) and RGS4 can inhibit several pain modulating receptors (e.g.  $\mu$ -opioid receptor) (Garnier et al., 2003; Traynor and Neubig, 2005). Consequently, small molecule modulators of RGS function should have utility as research tools and potentially as therapeutics. Due to the wealth of information on the structure and function of RGS4, we chose this protein as our primary target for validating the druggability of RGS proteins.

There have been several reported peptide inhibitors of RGS4 and related family members (Roof et al., 2006; Roof et al., 2008; Wang et al., 2008) and one disclosed small molecule inhibitor (Roman et al., 2007). Due to the physical properties of the peptides, none of them function in a cellular environment unless they are introduced intracellularly (e.g. by dialysis via a patch pipette (Roof et al., 2006)). The small molecule compound CCG-4986 irreversibly inhibits RGS4 by reacting with one or more cysteine residues (Kimple et al., 2007) and (Roman, Blazer & Neubig, in revision)) and its activity is lost in the presence of free thiols. This mechanism of

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action makes CCG-4986 less desirable as a potential lead compound for small molecule probe development. Consequently, we undertook this study to identify novel RGS inhibitors that retain activity under reducing conditions and ones that have a reversible mechanism of action.

This paper describes the identification and characterization of the first class of reversible small molecule inhibitors of an RGS protein. They were found in a biochemical high-throughput screen carried out in the presence of dithiothreitol (DTT). They inhibit the binding and GAP activity of RGS4 with  $G\alpha_o$  in a reversible manner through an interaction at an allosteric regulatory site on the RGS. These compounds represent an important step towards the development of tools for the study of RGS functions in physiological and pathophysiological situations.

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## Materials & Methods:

**Reagents:** Chemicals were purchased from Sigma-Aldrich (St. Louis, MO) or Fisher Scientific (Hampton, NH) and were reagent grade or better. AlexaFluor™-488 succinimidyl ester and LanthaScreen™ Thiol reactive Tb chelate were obtained from Invitrogen (Carlsbad, CA).  $\gamma$ [<sup>32</sup>P]GTP (10 mCi/mL) and [<sup>35</sup>S]GTP $\gamma$ S (12.5 mCi/mL) were obtained from Perkin Elmer Life and Analytical Sciences, (Boston, MA) and were isotopically diluted with unlabeled nucleotide before use. Amylose resin was purchased from New England Biolabs (Ipswich, MA). Ni-NTA resin was purchased from Qiagen (Valencia, CA). Avidin-coated microspheres were purchased from Luminex (Austin, TX). The screening library was comprised of a commercially available subset of compounds from Chem Div (San Diego, CA) provided through a collaboration between the University of Michigan Center for Chemical Genomics and the Novartis Institute for Biomedical Research. CCG-63802 (((2E)-2-(1,3-benzothiazol-2-yl)-3-[9-methyl-2-(3-methylphenoxy)-4-oxo-4H-pyrido[1,2-a]pyrimidin-3-yl]prop-2-enenitrile)) and CCG-63808 (((2E)-2-(1,3-benzothiazol-2-yl)-3-[9-methyl-2-(4-fluorophenoxy)-4-oxo-4H-pyrido[1,2-a]pyrimidin-3-yl]prop-2-enenitrile)) (see structures in Figure 1) were purchased from ChemDiv (San Diego, CA) and compound identity was verified by NMR via ChemDiv and by independent complete synthesis in the laboratory of Dr. Steven Husbands (University of Bath).

**Compound synthesis:** Briefly, 2-Hydroxy-9-methyl-4H-pyrido[1,2- $\alpha$ ]pyrimidin-4-one was prepared by the reaction of 2-amino-3-methylpyridine with diethyl malonate according to literature methods (Ingalls EA, 1967). This material was firstly converted to 2-chloro-9-methyl-4-oxo-4H-pyrido[1,2- $\alpha$ ]pyrimidine-3-carbaldehyde via Vilsmeier formylation, and this product was then heated with 4-fluorophenol to afford 2-(4-fluorophenoxy)-9-methyl-4-oxo-4H-

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pyrido[1,2- $\alpha$ ]pyrimidine-3-carbaldehyde. Condensation of this compound with 2-benzothiazole acetonitrile using catalytic triethylamine in dichloromethane provided CCG-63808 as an orange crystalline solid (Supplemental Fig. 1). CCG-63802 was prepared in a similar manner, except 4-fluorophenol was replaced with 3-methylphenol. Synthesized compounds were verified by  $^1\text{H}$  and  $^{13}\text{C}$  NMR using Jeol Delta-270-MHz instrument:  $^1\text{H}$  at 270 MHz, and Varian Mercury-400-MHz instrument:  $^1\text{H}$  at 400 MHz,  $^{13}\text{C}$  at 100 MHz;  $\delta$  in ppm, J in Hz with TMS as an internal standard, by electrospray mass spectrometry using micrOTOF (Bruker, Billerica, MA), and by microanalysis using a Perkin-Elmer 240C analyzer (Perkin-Elmer, Boston, MA).

**Protein expression & purification:** Human RGS4 was expressed either from the pQE80RGS4 vector, which encodes 6x histidine tagged and N-terminally truncated form of RGS4 that lacks the first 18 residues ( $\Delta\text{N19RGS4}$ ) or from the pKMRGS4 vector, which encodes a maltose-binding protein- $\Delta\text{N19RGS4}$  fusion protein. The  $\Delta\text{N}$  form of RGS4 was selected because it provides better protein yield in prokaryotic expression systems. MBP-His6-RGS19 $\Delta\text{C11}$  (human), MBP-His6-RGS7 (human), MBP-His6-RGS8 (human) and MBP-His6-RGS16 (human) were expressed from constructs made with the pMALC2H10 vector as previously described (Roman et al., 2009). For the mutagenesis studies,  $\Delta\text{N51RGS4}$  (rat) wild type and cysteine  $\rightarrow$  alanine mutants were expressed from the pMALC2H10 vector. Mutagenesis was performed as described (Roman, Blazer & Neubig, in revision) using the QuickChange Multi Site Directed Mutagenesis kit (Agilent, La Jolla CA) where one or more of the cysteine residues in the RGS domain of RGS4 were mutated to alanine.

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All proteins were expressed in and harvested from BL21-DE3 *E. coli* via standard transformation, growth, and lysis protocols (Lan et al., 1998; Lan et al., 2000; Lee et al., 1994; Roman et al., 2007; Roof et al., 2008). Histidine-tagged RGS4 was purified over a Nickel NTA affinity column (Qiagen, Valenica, CA) followed by cation exchange chromatography and size exclusion chromatography. MBP-tagged RGS proteins were purified with an amylose affinity column followed by size exclusion chromatography. Hexahistidine-tagged rat  $G\alpha_o$  was expressed and purified as previously described (Lee et al., 1994). G protein activity was determined by [ $^{35}$ S]GTP $\gamma$ S binding (Sternweis and Robishaw, 1984). In all cases, proteins were purified to >90% homogeneity before use.

**Chemical labeling of purified  $G\alpha_o$  & RGS:** AlexaFluor-488 labeling of RGS4:  $\Delta$ N19RGS4 was labeled with AlexaFluor-488 succinimidyl ester (Invitrogen, Carlsbad CA) at a 5:1 (label:protein) stoichiometry in a total volume of 2.0 mL of 50 mM HEPES pH 8.2 at 4°C, 100 mM NaCl, 1 mM DTT. The reaction was performed while rotating samples in the dark for 1.5 hr at 4°C. The reaction was quenched by the addition of 1 mM glycine for 10 minutes at 4°C. Labeled RGS4 was resolved from the reaction mixture by size exclusion chromatography using a 20 mL Sephadex G-25 desalting column (GE Biosciences, Piscataway NJ). Degree of labeling was determined spectroscopically to be approximately 1:1.

Tb chelate labeling of  $G\alpha_o$ :  $G\alpha_o$  was labeled with the Lanthascreen™ Tb thiol reactive reagent (Invitrogen, Carlsbad CA) at a 5:1 (label:protein) stoichiometry in a total volume of 1.0 mL of 50 mM HEPES pH 7.25 at 4°C, 100 mM NaCl, supplemented with 10  $\mu$ M GDP and 0.8 mM TCEP. The reaction was allowed to proceed at 4°C for 1.5 hr while rotating in the dark. The reaction

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was quenched by the addition 1 mM DTT for 20 minutes at 4°C. Labeled protein was purified from the reaction mixture by size exclusion chromatography using a Sephadex G-25 desalting column (GE Biosciences, Piscataway NJ). Degree of labeling was determined spectroscopically to be approximately 1:1. The activity and effective concentration of the labeled G protein was determined by [<sup>35</sup>S]GTPγS binding as described (Sternweis and Robishaw, 1984).

**Biotinylation of RGS proteins:** RGS protein was mixed at a 3:1 (label:protein) molar ratio with biotinamidohexanoic acid *N*-hydroxysuccinimide ester (Sigma, St. Louis, MO) in a buffer of 50 mM HEPES pH 8.5 at 4°C, 100 mM NaCl, & 1 mM DTT. The reaction was allowed to proceed at 4°C while rotating for 2 hours and then was quenched by the addition of a large molar excess of glycine for 10 minutes. Labeled protein was purified from the reaction mixture by size exclusion chromatography using a Sephadex G-25 desalting column (GE Biosciences, Piscataway NJ).

**AlexaFluor-532 labeling of Gα<sub>o</sub>:** Gα<sub>o</sub> labeling was performed as previously described (Roman et al., 2007). Labeled protein was purified from the reaction mixture by size exclusion chromatography using a Sephadex G-25 desalting column (GE Biosciences, Piscataway NJ).

**Time Resolved FRET:** TR-FRET experiments were performed on a PHERAstar multipurpose microplate reader (BMG Labtech, Offenberg, Germany) using the LanthaScreen filter set. These experiments were based on the method of Leifert et al (Leifert et al., 2006). For the saturation experiments, Tb-Gα<sub>o</sub> was diluted to 20 nM in 50 mM HEPES pH 8.0, 100 mM NaCl, 0.1% lubrol, 30 μM GDP, 5 mM NaF, 5 mM MgCl<sub>2</sub>, 5 μM AlCl<sub>3</sub> and allowed to activate for 10

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minutes on ice before use. RGS4-AF488 was serially diluted in 50 mM HEPES pH 8.0 at room temperature, 100 mM NaCl, 0.1% lubrol (TR-FRET buffer). Ten microliters of the RGS4 dilution was added to a black non-stick low-volume 384 well plate (Corning 3676) with a minimum of duplicate measurements. Ten microliters of the Tb-G $\alpha_o$  was added (10 nM final) and the mixture was allowed to incubate at room temperature for 15 minutes in the dark. The non-specific TR-FRET signal was determined by excluding the AlCl<sub>3</sub>, MgCl<sub>2</sub> and NaF from a set of samples. The fluorescence emission at both 490 and 520nm was measured from 50 flashes of 340 nm excitation light per well. The data were collected in 10  $\mu$ s bins and the delayed emission signal was integrated from 100 to 500  $\mu$ s after each flash. TR-FRET data was analyzed as the ratio of emission at 520 nm/490 nm.

**High Throughput Screening:** High throughput screening was performed with the University of Michigan Center for Chemical Genomics. The ca. 40,000 compound screening collection was provided by the Novartis Institute for Biomedical Research (East Hanover NJ) and was comprised of compounds selected from the ChemDiv screening library. Five microliters of 50 mM HEPES pH 8.0 at room temperature, 100 mM NaCl, 0.1% lubrol, 1 mM DTT (TR-FRET buffer) was dispensed with a Multidrop™ (Thermo Fisher Scientific, Waltham MA) into every well of a black, non-stick, low-volume 384-well plate. Two hundred nanoliters of each compound (2 mM stock, 20  $\mu$ M final assay concentration) or DMSO control was added to the plate with a pin tool using a Beckman BioMek FX liquid handler (Beckman Coulter, Fullerton, CA). To this compound dilution, 5 microliters of 200 nM AlexFluor 488 labeled RGS4 was added and incubated for 15 minutes at room temperature in the dark. Then, 10 microliters of 20 nM Tb labeled G $\alpha_o$  was added to the mixture. For this assay, the positive inhibition control (i.e.

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no RGS4/ $G\alpha_o$  binding) was Tb-labeled  $G\alpha_o$  in the inactive GDP-bound state and the negative control (i.e. full RGS4/ $G\alpha_o$  binding) utilized  $G\alpha_o$  in the GDP/ $AlF_4$  bound state. This mixture was incubated at room temperature in the dark for 15 minutes before analysis with the PHERAstar plate reader. Data were compiled and analyzed using the M-Screen database, an in-house chemoinformatics suite developed by the Center for Chemical Genomics at the University of Michigan. Compounds that inhibited the TR-FRET signal  $>2SD$  from the negative control were considered “actives” and were chosen for dose response follow-up experiments.

**TR-FRET Dose Response Experiments:** Actives from the primary screen were evaluated for concentration-dependent activity in the TR-FRET assay. Compound dilutions were performed in DMSO and 200 nL of diluted compound was spotted into the wells of a non-stick, low volume black 384-well plate that contained 5  $\mu$ L of TR-FRET buffer. To the well, 5  $\mu$ L of 200 nM AlexFluor 488 labeled RGS4 was added and incubated at room temperature in the dark for 15 minutes. Then, 10  $\mu$ L of 20 nM Tb labeled  $G\alpha_o$  GDP/ $AlF_4$  was added to the mixture and incubated at room temperature in the dark for 30 minutes before analysis on the PHERAstar plate reader. Compound dilutions covered a final concentration range from 200  $\mu$ M to 1.6  $\mu$ M. Positive and negative controls were performed as in the primary screening assay. Compounds whose dose response curves were not fully defined by these concentrations were repeated using a more appropriate dilution scheme. Nonlinear least-squares regression fitting of the data was performed using the data analysis component of the MScreen database.

**Flow Cytometry Protein Interaction Assay Concentration Dependence Experiments:**

Compounds that confirmed in the follow up TR-FRET dose response assay were tested as

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described (Roman et al., 2007) in the Flow Cytometry Protein Interaction Assay (FCPIA). This was done in part to provide a complementary set of biochemical data to filter out any compounds that might produce spectroscopic artifacts in the TR-FRET assay. Briefly, biotinylated RGS proteins (5nM, final assay concentration) were immobilized on Luminex LumAvidin beads and incubated with diluted compound in 50 mM HEPES pH 8.0 at room temperature, 100 mM NaCl, 0.1% lubrol, 1 mM DTT, supplemented with 1% BSA. To each well of a 96-well PCR plate (Axygen, Union City, CA) was added AlexaFluor 532 labeled  $G\alpha_o$  to a final concentration of 30nM. This mixture was incubated for 30 minutes at room temperature in the dark and then it was analyzed on a Luminex 200 flow cytometer for the bead associated fluorescence (median value). Nonlinear regression analysis of inhibition curves was performed with Prism 5.0 (Graphpad Software, San Diego CA).

**FCPIA Reversibility Experiments:** RGS-coated beads were prepared as above and were treated with 50  $\mu$ M compound or vehicle (DMSO) for 15 minutes at room temperature. The RGS-containing beads were then washed by resuspension in 1mL of phosphate buffered saline, pH 7.4 supplemented with 1% BSA, vortexing briefly, then pelleting the beads by centrifugation. This procedure was repeated a total of three times before 1,000 beads were added to each quadruplicate well of a 96-well PCR plate that contained AlexaFluor-532-labeled  $G\alpha_o$  at a final concentration of 20 nM in the presence or absence of 50 $\mu$ M test compound. The mixture was incubated for 30 minutes at room temperature and then analyzed on a Luminex 200 flow cytometer for bead-associated fluorescence. Data analysis was performed with Prism 5.0 (Graphpad Software, San Diego CA).

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**Single Turnover GTPase Measurements:** Compounds were tested for the ability to inhibit the RGS4-stimulated increase in GTP hydrolysis by  $G\alpha_o$  as described previously (Roman et al., 2007; Roof et al., 2006).

**Thermal Stability Measurements:** Untagged  $\Delta N19RGS4$  or His<sub>6</sub>- $G\alpha_o$  was added to the well of a 96-well ABI Prism optical reaction plate (Applied Biosystems, Foster City CA) to a final concentration of 5 or 2.5  $\mu M$ , respectively in 50-60  $\mu L$  of 50 mM HEPES pH 8.0 with 150 mM NaCl. Test compounds were added to the protein at the desired concentration and allowed to interact for 15 minutes at room temperature. To each well, Sypro Orange dye (Invitrogen, Carlsbad, CA) was added to a 5X final concentration (as described by the supplier) and the plate was sealed with an optically clear adhesive film. Sypro Orange fluorescence was measured continuously in an ABI HT7900 real-time PCR system during a stepwise gradient from ambient temperature to 90°C in 1°C steps lasting 30 seconds each. Data are analyzed by fitting the obtained curves to a Boltzmann model (Eqn. 1):

$$\text{(Eqn. 1)} \quad I = L \frac{(U - L)}{1 + e^{-\frac{(T_m - T)}{a}}}$$

Where I = Fluorescence Intensity (AU), L = the lower limit of the curve (°C), U = the upper limit of the curve (°C), T = temperature (°C), and a = is a slope factor. Values obtained after the fluorescence maximum occurred were excluded from the analysis.

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## Results:

**Development of a High-Throughput TR-FRET RGS4-G $\alpha_o$  interaction screen:** We developed a biochemical TR-FRET assay using purified human RGS4 labeled with the AlexaFluor-488 acceptor fluorophore and purified G $\alpha_o$  labeled with the LanthaScreen Tb probe donor fluorophore (Fig. 1A). Using this system, we observed a saturable, aluminum fluoride-dependent interaction between RGS4 and G $\alpha$  that has an affinity consistent with other reports of this PPI in the literature (Fig. 1B) (Roman et al., 2007). In collaboration with the Center for Chemical Genomics at the University of Michigan, this assay was scaled to 384-well format and used to screen ~44,000 small molecules for inhibition of RGS4/G $\alpha_o$  binding in the presence of a thiol reducing agent (Table 1). Compounds from this screen were re-tested in the primary screening assay to confirm the initial result and to assess the concentration dependence of the inhibition using the original TR-FRET assay. Of the 162 compounds that met the 2SD selection criteria for inhibition, 48 were either unavailable or predicted to be chemically reactive and were not followed-up. The 114 selected compounds were retested in TR-FRET DRC and 11 were confirmed as inhibitors with IC<sub>50</sub> values <400  $\mu$ M and Hill Slopes <2.

The confirmed, active compounds were obtained from the supplier as fresh powders and tested using the Flow Cytometry Protein Interaction Assay (FCPIA), a method that measures the binding of fluorescently tagged G $\alpha_o$  to an RGS protein on beads (Roman et al., 2007). Of the 11 compounds tested, 2 showed similar activity on RGS4 in both the TR-FRET dose response and FCPIA experiments (Fig. 1C). The 9 compounds that did not show activity in this secondary assay are presumed to have been spectral artifacts or small molecule aggregators that are likely

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to lose function in the relatively stringent conditions of the FCPIA assay buffer (50 mM HEPES, 100 mM NaCl, 1% BSA and 0.1% lubrol, pH 8.0).

The two active compounds that were identified from this primary screen were the closely related CCG-63808 and CCG-63802 (Fig. 1D). These compounds differ solely by the substituents on the phenyl moiety and have similar  $IC_{50}$  values in TR-FRET and FCPIA. The compounds also contain a vinyl cyanide moiety that may function as a reversible Michael acceptor.

**CCG-63802 & CCG-63808 selectively inhibit  $G\alpha_o$ -RGS interactions:** Using TR-FRET to assess the RGS4- $G\alpha_o$  interaction, CCG-63802 and CCG-63808 had  $IC_{50}$  values of 1.9 and 1.4  $\mu$ M, respectively (Fig. 1C). To determine the selectivity of these compounds for different RGS proteins, they were tested in an FCPIA competition experiment against a panel of 5 different RGS proteins (Fig. 2, Table 2). The compounds are 6- to 7-fold less potent in blocking  $G\alpha_o$ /RGS4 interactions when tested using FCPIA ( $IC_{50}$  ~10  $\mu$ M) than with the TR-FRET method. This is probably due to the high level of BSA (1%) in the FCPIA buffer sequestering compound and decreasing its apparent concentration in the assay. These compounds did not inhibit  $G\alpha$  binding to RGS7, which is distantly related to RGS4, and they are two- to ten-fold more potent at RGS4 than on the other closely related R4 family members, RGS8 and RGS16 (Table 2). They are also fairly active ( $IC_{50}$  20-50  $\mu$ M) on the one RZ family member tested, RGS19.

**CCG-63802 & CCG-63808 inhibit RGS4 GAP activity:** For RGS inhibitors to be functionally relevant, they need to inhibit the catalytic activity of the RGS in addition to blocking  $G\alpha$ /RGS

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binding. The two compounds inhibit the GAP activity of RGS4 as shown by measurements using the [<sup>32</sup>P]GTP single turnover GAP assay (Fig. 3). Under these conditions, GTP hydrolysis by Gα<sub>o</sub> is accelerated ~10-fold by the addition of wtRGS4 and this effect can be inhibited by the previously described (Roman et al., 2007) RGS4 inhibitor CCG-4986. At a concentration of 50 μM, CCG-63802 and CCG-63808 fully inhibit the RGS activity without affecting basal Gα<sub>o</sub> GTPase activity.

**CCG-63802 & CCG-63808 bind to RGS4 but not to Gα<sub>o</sub>:** Since the studies presented so far assessed the binary interaction between two purified proteins, it was necessary to determine to which protein the compounds bound. The specificity for RGS4 over RGS7, 8, and 19 suggested, but did not prove that the compounds bound to the RGS rather than to the Gα<sub>o</sub>. To directly identify the site of action of these compounds, we developed a thermal denaturation assay to assess compound binding. This methodology is based on the principal that the stability of a protein is often altered upon ligand binding (Lo et al., 2004; Senisterra et al., 2008). For proteins that have endogenous small molecule or peptide ligands (e.g. enzymes or receptors), binding of the ligand often increases the thermal stability. Upon binding GDP, Gα<sub>o</sub> experiences a >5°C increase in melting temperature (T<sub>m</sub>) when compared to nucleotide-free protein (Supplemental Fig. 2). This increases to a >20°C increase in T<sub>m</sub> for Gα<sub>o</sub> binding the exceptionally high affinity nucleotide GTPγS. Using this assay, we observed a concentration-dependent 10°C reduction (See Discussion) in the melting temperature of RGS4 in the presence of CCG-63802 (Fig. 4A). The concentration dependence of this effect corresponds with the IC<sub>50</sub> values obtained in the FCPIA assay. Even at a maximal concentration of CCG-63802 (100 μM), there was no change in the melting temperature of Gα<sub>o</sub> (Fig. 4B).

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**CCG-63802 and CCG-63808 are reversible inhibitors of the  $G\alpha_o$ -RGS interaction:** The effects of CCG-4986, our previously described RGS4 inhibitor (Roman et al., 2007), could not be reversed by dilution and washing away the compound, showing that it acts irreversibly to inhibit the function of RGS4 ((Kimple et al., 2007), (Roman, Blazer & Neubig, in revision), and Fig. 5). Also, its activity was blocked in the presence of reducing agents. These effects are likely due to the formation of a covalent adduct of the compound with a cysteine residue in the RGS ((Kimple et al., 2007) and (Roman, Blazer & Neubig, in revision)). Since our new compounds were identified through screens in the presence of DTT, we tested the reversibility of their inhibition. RGS-coated microspheres were treated with 50  $\mu$ M compound or vehicle (DMSO), extensively washed (see Methods for details), and then assayed for  $G\alpha_o$  binding (Fig. 5). In contrast to the effects of CCG-4986, full binding was restored to compound-treated RGS-beads after washing (Fig. 5), showing that CCG-63802 and CCG-63808 are reversible on the 10 minute time scale required for the washing procedure. Consequently, these new compounds represent the first examples of reversible small molecule inhibitors of an RGS protein.

**Cysteine Dependence of CCG-63802 and CCG-63808:** To further explore the mechanism of these compounds and the role of cysteines in their action, they were tested on a mutant of RGS4 where all cysteines in the RGS domain were mutated to alanine (RGS4c). In FCPIA measures of  $G\alpha$  binding to RGS4c, CCG-63802 and CCG-63808 show only modest activity, indicating a role for RGS cysteines in the actions of these compounds (Supplemental Fig. 3, Table 3). Consequently, we tested CCG-63808 and CCG-63802 with a panel of RGS4 RGS domain cysteine mutants using FCPIA (Table 3). The G protein binding affinity of these RGS mutants

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has been previously described (Roof et al., 2009) and the  $K_d$  values ranged from 3-12 nM, not drastically different from that of wild type RGS4. No single cysteine could fully account for the effects of these compounds, but it appears that three cysteines, Cys 148, Cys 132, and Cys 95 are important for full sensitivity to CCG-63808 and CCG-63802. Cysteine 95 and Cys 148 are located rather close to each other on RGS4, however they are at a site distinct from the  $G\alpha$  interaction interface. It appears that Cys 95 plays a more significant role than Cys 148, possibly suggesting that the compound docks onto the RGS at a site that is either closer to this cysteine or that requires this residue for proper formation of the compound binding pocket.

Since thiol-reactive compounds may have difficulty functioning in the reducing environment of a cell, it is important to assess the activity of any such leads under conditions mimicking the intracellular environment. Therefore, CCG-63802, CCG-63808, and CCG-4986 were tested for activity using FCPIA in the presence of 2 mM reduced glutathione (Fig. 6). This concentration of glutathione was selected because it is similar to intracellular concentrations. CCG-63802 and CCG-63808 lose approximately 0.5-1 Log of potency ( $IC_{50}$  6  $\mu$ M  $\rightarrow$  40  $\mu$ M for CCG-63802; 4  $\mu$ M  $\rightarrow$  21  $\mu$ M for CCG-63808) in the presence of 2 mM glutathione, but still retain the ability to fully inhibit the interaction between RGS4 and  $G\alpha_o$ . In contrast, CCG-4986 loses over 2-Logs in potency ( $IC_{50}$  from 1.4  $\mu$ M  $\rightarrow$  215  $\mu$ M) in the presence of 2 mM glutathione and it is not capable of fully inhibiting the RGS- $G\alpha_o$  interaction up to concentrations nearing its aqueous solubility (Fig. 6).

Interestingly, CCG-63802 and CCG-63808 inhibit the GAP activity of RGS4c (Fig. 7) mutant despite their much lower potency to inhibit  $G\alpha_o$ /RGS4c binding in FCPIA (Supplemental Fig. 3).

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Thus these compounds can inhibit the functional activity of the cysteine-null RGS4 mutant, while having much less effect on the high-affinity binding to GDP-AMF bound  $G\alpha_o$  (see Discussion). This inhibitory effect does not appear to be due to compound aggregation, as is not reversed in the presence of 0.01% Triton (data not shown), which generally blocks the activity of promiscuous small molecule aggregators (Feng et al., 2007).

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### **Discussion:**

RGS proteins play a strong modulatory role in GPCR signaling leading to substantial interest in small molecule inhibitors targeting this class of proteins (Blazer and Neubig, 2009; Neubig and Siderovski, 2002; Zhong and Neubig, 2001); (Riddle et al., 2005; Traynor et al., 2009). The localized expression of RGS proteins (Kurrasch et al., 2004) suggested that RGS inhibitors could provide enhanced tissue specificity for GPCR agonist actions (Blazer and Neubig, 2009; Neubig and Siderovski, 2002; Zhong and Neubig, 2001). Furthermore, up-regulation of RGS proteins in various disease states, for example RGS4 in neuropathic pain models (Garnier et al., 2003), also provides an important rationale for targeting RGS proteins. In this study, we report the second family of RGS SMPPIIs. Unlike the our previously reported RGS inhibitor, CCG-4986 (Roman et al., 2007) which is irreversible and loses function in the presence of reducing agents ((Kimple et al., 2007) and (Roman, Blazer & Neubig, in revision)), the new compounds identified here, act reversibly and function in the presence of glutathione, a predominant intracellular reductant. These compounds, with their reversibility and activity in glutathione, therefore represent a significant step forward in the development RGS SMPPIIs.

Similar to our original compound, CCG-63802 and CCG-63808 are relatively selective for RGS4 over other R4 family members, including the closely related RGS8 and RGS16. They have no detectable activity for the more distantly related RGS7. They also have some dependence on cysteine residues since they very weakly inhibit the cysteine-null (C→A) mutant of RGS4 (RGS4c) in the FCPIA assay. However, both compounds at 50 μM fully inhibit the GAP activity of RGS4c. There are a few potential explanations for this discrepancy. First, the compounds, which are of modest affinity (~10 μM) in the FCPIA studies, may have a very short RGS-bound

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lifetime and therefore have difficulty competing with the constitutive binding of  $\text{AlF}_4^-/\text{GDP}$ -bound  $\text{G}\alpha_o$  to the RGS. In the GTPase assay they may be more efficient at inhibiting the transient interaction between GTP-bound  $\text{G}\alpha_o$  and RGS4 during the catalytic cycle. Also, since the compounds appear to act via an allosteric site (see below), the induced conformational change in RGS4 may have a more dramatic impact on binding to or GAP activity at the  $\text{G}\alpha$ -GTP than for the  $\text{GDP-AlF}_4^-$  conformation of the  $\text{G}\alpha$  subunits. Indeed, it is the effects of compounds on RGS GAP activity and not on  $\text{G}\alpha$  binding that are most relevant in cellular or animal models.

The partial cysteine-dependence of the actions of these compounds suggests a tethering model in which a reactive group binds to RGS cysteine residue(s). This is supported by the cysteine mutagenesis studies and also by the presence of the potential Michael acceptor functionality (vinyl cyanide) in both of the compounds. Tethered ligands can provide enhanced potency for small molecules acting on difficult targets (Arkin et al., 2003; Erlanson et al., 2000). Our ability to detect these compounds may have derived from potency enhancement from a slow off-rate due to tethering. The reaction, however, is clearly reversible on the 10-minute time scale and attempts to demonstrate covalent binding by mass spectroscopy have been unsuccessful. While uncommon, there are other well-described examples of reversible Michael acceptor reactions with thiols (Ettari et al., 2008; Jin et al., 2007). While most drug molecules are designed to avoid such reactive groups, there are a number of examples of clinically used drugs (e.g. omeprazole) or drug candidates (CI-1033) that are thiol reactive (Ocana and Amir, 2009; Sachs et al., 1994). Furthermore, tethered ligands have been used to develop SAR in the context of the higher affinity starting structure that is then transferred to analogs without the reactive group (Erlanson

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et al., 2003). The activity of CCG-63802 and CCG-63808 to inhibit the GAP activity of RGS4c suggests that this may be a reasonable approach.

The compounds described here require three cysteines for full potency of RGS4 inhibition: cys 95, cys 148 and cys 132. Cysteines 95 and 148 are positioned in the “B site” of RGS proteins (Zhong and Neubig, 2001) which is proposed to participate in the allosteric modulation of RGS4 by acidic phospholipids and calmodulin (Ishii et al., 2005a; Popov et al., 2000). Cysteine 132 is located on the outer edge of the  $G\alpha$  interaction interface and, at high concentrations, may react with CCG-63802 in a reversible Michael reaction to provide modest steric occlusion of the protein-protein interaction. Consequently, these compounds appear to have both allosteric and steric elements in their mechanism.

The binding of CCG-63802 induces a destabilizing effect on RGS4 in the thermal stability studies. This contrasts with the stabilizing effect observed (Grasberger et al., 2005; Wan et al., 2009) for small molecule ligand binding to many proteins (e.g.  $G\alpha_o$ , Supplemental Fig 2). We observed that this family of compounds causes a left shift in the melting curve to lower temperatures. This reduced stability of the RGS4 may be related to conformational perturbation induced upon compound binding to the cysteines in the allosteric site.

In most instances, proteins with endogenous small molecule ligands (e.g.  $G\alpha$  proteins) are stabilized by the presence of their ligand (Grasberger et al., 2005; Wan et al., 2009). This notion was recently borne out by the recent crystallization of several GPCRs (Cherezov et al., 2007; Jaakola et al., 2008; Rasmussen et al., 2007; Scheerer et al., 2008; Warne et al., 2008). In all

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cases (the notable exception being opsin), crystals were only obtained in the presence of – among other reagents – a small molecule ligand. This strongly suggests that these ligands are important for the structural stability of this class receptor in solution. Furthermore, our data (Supplemental Fig. 2) and others (Abad et al., 2008; Matulis et al., 2005) also confirm that binding of natural or artificial ligands to sites that have evolved the capacity for small molecule binding causes a stabilization of the protein. This stabilizing effect may be due to the decrease in free energy derived from the binding event and also the conformational restriction required for high-affinity ligand-protein interaction. This increased protein rigidity is likely to provide a level of protection against the increasingly intense thermally-induced conformational fluctuations as the temperature of the sample is raised.

On the surface, it would appear that this paradigm is contradicted by the compounds CCG-63802 and CCG-63808 which potently destabilize RGS4 even though they appear to bind close to the site on RGS4 that binds native acidic phospholipids. It is possible that these compounds bind to a site near, yet independent of, the acidic lipid site on the RGS and binding to this non-natural site might not be expected to produce the same stabilization effect as binding of small molecules to sites that have evolved the capacity for such small molecule-protein interactions. Also, insertion of the compounds into the 4-helix bundle, stabilized by the reversible Michael addition to a cysteine thiol, could unfold the RGS4 structure leading to destabilization.

In this study we have identified the first examples of reversible SMPPIIs that disrupt RGS protein function. CCG-63808 and CCG-63802 are selective inhibitors of the RGS-G $\alpha$  interaction and R4 family GAP activity. Their mechanism appears to, at least in part, involve an allosteric

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action at the “B” site on the RGS (Zhong and Neubig, 2001), which has been implicated in the physiological allosteric modulation of RGS proteins by acidic phospholipids and calmodulin (Ishii et al., 2005a; Ishii et al., 2005b). Further studies of the mechanism and structure-activity relationships for this compound class and translation to cellular and animal models of RGS function are currently underway.

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## References:

- Abad MC, Askari H, O'Neill J, Klinger AL, Milligan C, Lewandowski F, Springer B, Spurlino J and Rentzeperis D (2008) Structural determination of estrogen-related receptor gamma in the presence of phenol derivative compounds. *J Steroid Biochem Mol Biol* **108**(1-2):44-54.
- Arkin MR, Randal M, DeLano WL, Hyde J, Luong TN, Oslob JD, Raphael DR, Taylor L, Wang J, McDowell RS, Wells JA and Braisted AC (2003) Binding of small molecules to an adaptive protein-protein interface. *Proc Natl Acad Sci U S A* **100**(4):1603-1608.
- Arkin MR and Wells JA (2004) Small-molecule inhibitors of protein-protein interactions: progressing towards the dream. *Nat Rev Drug Discov* **3**(4):301-317.
- Arkin MR and Whitty A (2009) The road less traveled: modulating signal transduction enzymes by inhibiting their protein-protein interactions. *Curr Opin Chem Biol* **13**(3):284-290.
- Berg T (2003) Modulation of protein-protein interactions with small organic molecules. *Angew Chem Int Ed Engl* **42**(22):2462-2481.
- Berg T (2008) Small-molecule inhibitors of protein-protein interactions. *Curr Opin Drug Discov Devel* **11**(5):666-674.
- Berman DM, Kozasa T and Gilman AG (1996) The GTPase-activating protein RGS4 stabilizes the transition state for nucleotide hydrolysis. *J Biol Chem* **271**(44):27209-27212.
- Blazer LL and Neubig RR (2008) Small Molecule Protein-Protein Interaction Inhibitors as CNS Therapeutic Agents: Current Progress and Future Hurdles. *Neuropsychopharmacology*.
- Blazer LL and Neubig RR (2009) Small molecule protein-protein interaction inhibitors as CNS therapeutic agents: current progress and future hurdles. *Neuropsychopharmacology* **34**(1):126-141.

MOL #65128

Bueno L and Fioramonti J (1988) Action of opiates on gastrointestinal function. *Baillieres Clin Gastroenterol* **2**(1):123-139.

Busschots K, De Rijck J, Christ F and Debyser Z (2009) In search of small molecules blocking interactions between HIV proteins and intracellular cofactors. *Mol Biosyst* **5**(1):21-31.

Cherezov V, Rosenbaum DM, Hanson MA, Rasmussen SG, Thian FS, Kobilka TS, Choi HJ, Kuhn P, Weis WI, Kobilka BK and Stevens RC (2007) High-resolution crystal structure of an engineered human beta2-adrenergic G protein-coupled receptor. *Science* **318**(5854):1258-1265.

Erlanson DA, Braisted AC, Raphael DR, Randal M, Stroud RM, Gordon EM and Wells JA (2000) Site-directed ligand discovery. *Proc Natl Acad Sci U S A* **97**(17):9367-9372.

Erlanson DA, Lam JW, Wiesmann C, Luong TN, Simmons RL, DeLano WL, Choong IC, Burdett MT, Flanagan WM, Lee D, Gordon EM and O'Brien T (2003) In situ assembly of enzyme inhibitors using extended tethering. *Nat Biotechnol* **21**(3):308-314.

Ettari R, Nizi E, Di Francesco ME, Dude MA, Pradel G, Vicik R, Schirmeister T, Micale N, Grasso S and Zappala M (2008) Development of peptidomimetics with a vinyl sulfone warhead as irreversible falcipain-2 inhibitors. *J Med Chem* **51**(4):988-996.

Feng BY, Simeonov A, Jadhav A, Babaoglu K, Inglese J, Shoichet BK and Austin CP (2007) A high-throughput screen for aggregation-based inhibition in a large compound library. *J Med Chem* **50**(10):2385-2390.

Gadek TR and Nicholas JB (2003) Small molecule antagonists of proteins. *Biochem Pharmacol* **65**(1):1-8.

Garnier M, Zaratin PF, Ficalora G, Valente M, Fontanella L, Rhee MH, Blumer KJ and Scheideler MA (2003) Up-regulation of regulator of G protein signaling 4 expression in a

MOL #65128

model of neuropathic pain and insensitivity to morphine. *J Pharmacol Exp Ther* **304**(3):1299-1306.

Grasberger BL, Lu T, Schubert C, Parks DJ, Carver TE, Kobilsh HK, Cummings MD, LaFrance LV, Milkiewicz KL, Calvo RR, Maguire D, Lattanze J, Franks CF, Zhao S, Ramachandren K, Bylebyl GR, Zhang M, Manthey CL, Petrella EC, Pantoliano MW, Deckman IC, Spurlino JC, Maroney AC, Tomczuk BE, Molloy CJ and Bone RF (2005) Discovery and cocrystal structure of benzodiazepinedione HDM2 antagonists that activate p53 in cells. *J Med Chem* **48**(4):909-912.

Hollinger S and Hepler JR (2002) Cellular regulation of RGS proteins: modulators and integrators of G protein signaling. *Pharmacol Rev* **54**(3):527-559.

Huang X, Charbeneau RA, Fu Y, Kaur K, Gerin I, MacDougald OA and Neubig RR (2008) Resistance to diet-induced obesity and improved insulin sensitivity in mice with a regulator of G protein signaling-insensitive G184S Gnai2 allele. *Diabetes* **57**(1):77-85.

Huang X, Fu Y, Charbeneau RA, Saunders TL, Taylor DK, Hankenson KD, Russell MW, D'Alecy LG and Neubig RR (2006) Pleiotropic phenotype of a genomic knock-in of an RGS-insensitive G184S Gnai2 allele. *Mol Cell Biol* **26**(18):6870-6879.

Ingalls EA PF (1967) The Preparation, Structure, and Reactions of Some "Malonyl- $\alpha$ -aminopyridines". *J Heterocyclic Chem* **4**:523-526.

Ishii M, Fujita S, Yamada M, Hosaka Y and Kurachi Y (2005a) Phosphatidylinositol 3,4,5-trisphosphate and Ca<sup>2+</sup>/calmodulin competitively bind to the regulators of G-protein-signalling (RGS) domain of RGS4 and reciprocally regulate its action. *Biochem J* **385**(Pt 1):65-73.

MOL #65128

- Ishii M, Ikushima M and Kurachi Y (2005b) In vivo interaction between RGS4 and calmodulin visualized with FRET techniques: possible involvement of lipid raft. *Biochem Biophys Res Commun* **338**(2):839-846.
- Jaakola VP, Griffith MT, Hanson MA, Cherezov V, Chien EY, Lane JR, Ijzerman AP and Stevens RC (2008) The 2.6 angstrom crystal structure of a human A2A adenosine receptor bound to an antagonist. *Science* **322**(5905):1211-1217.
- Jin F, Jin XY, Jin YL, Sohn DW, Kim SA, Sohn DH, Kim YC and Kim HS (2007) Structural requirements of 2',4',6'-tris(methoxymethoxy) chalcone derivatives for anti-inflammatory activity: the importance of a 2'-hydroxy moiety. *Arch Pharm Res* **30**(11):1359-1367.
- Kimple AJ, Willard FS, Giguere PM, Johnston CA, Mocanu V and Siderovski DP (2007) The RGS protein inhibitor CCG-4986 is a covalent modifier of the RGS4 Galpha-interaction face. *Biochim Biophys Acta* **1774**(9):1213-1220.
- Kurrasch DM, Huang J, Wilkie TM and Repa JJ (2004) Quantitative real-time polymerase chain reaction measurement of regulators of G-protein signaling mRNA levels in mouse tissues. *Methods Enzymol* **389**:3-15.
- Lan KL, Sarvazyan NA, Taussig R, Mackenzie RG, DiBello PR, Dohlman HG and Neubig RR (1998) A point mutation in Galphao and Galphai1 blocks interaction with regulator of G protein signaling proteins. *J Biol Chem* **273**(21):12794-12797.
- Lan KL, Zhong H, Nanamori M and Neubig RR (2000) Rapid kinetics of regulator of G-protein signaling (RGS)-mediated Galphai and Galphao deactivation. Galpha specificity of RGS4 AND RGS7. *J Biol Chem* **275**(43):33497-33503.
- Lee E, Linder ME and Gilman AG (1994) Expression of G-protein alpha subunits in Escherichia coli. *Methods Enzymol* **237**:146-164.

MOL #65128

- Leifert WR, Bailey K, Cooper TH, Aloia AL, Glatz RV and McMurchie EJ (2006) Measurement of heterotrimeric G-protein and regulators of G-protein signaling interactions by time-resolved fluorescence resonance energy transfer. *Anal Biochem* **355**(2):201-212.
- Lo MC, Aulabaugh A, Jin G, Cowling R, Bard J, Malamas M and Ellestad G (2004) Evaluation of fluorescence-based thermal shift assays for hit identification in drug discovery. *Anal Biochem* **332**(1):153-159.
- Matulis D, Kranz JK, Salemme FR and Todd MJ (2005) Thermodynamic stability of carbonic anhydrase: measurements of binding affinity and stoichiometry using ThermoFluor. *Biochemistry* **44**(13):5258-5266.
- Neubig RR and Siderovski DP (2002) Regulators of G-protein signalling as new central nervous system drug targets. *Nat Rev Drug Discov* **1**(3):187-197.
- Niu G and Chen X (2009) From protein-protein interaction to therapy response: molecular imaging of heat shock proteins. *Eur J Radiol* **70**(2):294-304.
- Ocana A and Amir E (2009) Irreversible pan-ErbB tyrosine kinase inhibitors and breast cancer: current status and future directions. *Cancer Treat Rev* **35**(8):685-691.
- Popov SG, Krishna UM, Falck JR and Wilkie TM (2000) Ca<sup>2+</sup>/Calmodulin reverses phosphatidylinositol 3,4, 5-trisphosphate-dependent inhibition of regulators of G protein-signaling GTPase-activating protein activity. *J Biol Chem* **275**(25):18962-18968.
- Rasmussen SG, Choi HJ, Rosenbaum DM, Kobilka TS, Thian FS, Edwards PC, Burghammer M, Ratnala VR, Sanishvili R, Fischetti RF, Schertler GF, Weis WI and Kobilka BK (2007) Crystal structure of the human beta2 adrenergic G-protein-coupled receptor. *Nature* **450**(7168):383-387.

MOL #65128

Riddle EL, Schwartzman RA, Bond M and Insel PA (2005) Multi-tasking RGS proteins in the heart: the next therapeutic target? *Circ Res* **96**(4):401-411.

Roman DL, Ota S and Neubig RR (2009) Polyplexed Flow Cytometry Protein Interaction Assay: A Novel High-Throughput Screening Paradigm for RGS Protein Inhibitors. *J Biomol Screen*.

Roman DL, Talbot JN, Roof RA, Sunahara RK, Traynor JR and Neubig RR (2007) Identification of small-molecule inhibitors of RGS4 using a high-throughput flow cytometry protein interaction assay. *Mol Pharmacol* **71**(1):169-175.

Roof RA, Jin Y, Roman DL, Sunahara RK, Ishii M, Mosberg HI and Neubig RR (2006) Mechanism of action and structural requirements of constrained peptide inhibitors of RGS proteins. *Chem Biol Drug Des* **67**(4):266-274.

Roof RA, Roman DL, Clements ST, Sobczyk-Kojiro K, Blazer LL, Ota S, Mosberg HI and Neubig RR (2009) A covalent peptide inhibitor of RGS4 identified in a focused one-bead, one compound library screen. *BMC Pharmacol* **9**(1):9.

Roof RA, Sobczyk-Kojiro K, Turbiak AJ, Roman DL, Pogozheva ID, Blazer LL, Neubig RR and Mosberg HI (2008) Novel peptide ligands of RGS4 from a focused one-bead, one-compound library. *Chem Biol Drug Des* **72**(2):111-119.

Sachs G, Prinz C, Loo D, Bamberg K, Besancon M and Shin JM (1994) Gastric acid secretion: activation and inhibition. *Yale J Biol Med* **67**(3-4):81-95.

Scheerer P, Park JH, Hildebrand PW, Kim YJ, Krauss N, Choe HW, Hofmann KP and Ernst OP (2008) Crystal structure of opsin in its G-protein-interacting conformation. *Nature* **455**(7212):497-502.

MOL #65128

- Senisterra GA, Soo Hong B, Park HW and Vedadi M (2008) Application of high-throughput isothermal denaturation to assess protein stability and screen for ligands. *J Biomol Screen* **13**(5):337-342.
- Sternweis PC and Robishaw JD (1984) Isolation of two proteins with high affinity for guanine nucleotides from membranes of bovine brain. *J Biol Chem* **259**(22):13806-13813.
- Traynor JR and Neubig RR (2005) Regulators of G protein signaling & drugs of abuse. *Mol Interv* **5**(1):30-41.
- Traynor JR, Terzi D, Caldarone BJ and Zachariou V (2009) RGS9-2: probing an intracellular modulator of behavior as a drug target. *Trends Pharmacol Sci* **30**(3):105-111.
- Wan KF, Wang S, Brown CJ, Yu VC, Entzeroth M, Lane DP and Lee MA (2009) Differential scanning fluorimetry as secondary screening platform for small molecule inhibitors of Bcl-XL. *Cell Cycle* **8**(23):3943-3952.
- Wang Y, Lee Y, Zhang J and Young KH (2008) Identification of Peptides That Inhibit Regulator of G Protein Signaling 4 Function. *Pharmacology* **82**(2):97-104.
- Warne T, Serrano-Vega MJ, Baker JG, Moukhametzianov R, Edwards PC, Henderson R, Leslie AG, Tate CG and Schertler GF (2008) Structure of a beta1-adrenergic G-protein-coupled receptor. *Nature* **454**(7203):486-491.
- Zhong H and Neubig RR (2001) Regulator of G protein signaling proteins: novel multifunctional drug targets. *J Pharmacol Exp Ther* **297**(3):837-845.

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### Figure Legends:

**Figure 1.** Characterization of the RGS4 TR-FRET high-throughput Assay. A) Schematic of RGS4- $G\alpha_o$  TR-FRET assay.  $G\alpha_o$  is labeled with the LanthaScreen Tb-chelate donor fluorophore and RGS4 is labeled with an AlexaFluor-488 acceptor fluorophore. Excitation and emission maxima are listed for each fluorophore. B) Representative data showing the  $AlF_4^-/GDP$  dependence of the interaction between AF-488RGS4 and 10 nM of Tb- $G\alpha_o$ . This saturable interaction has a  $K_d$  of  $35\pm 4$  nM. C) Two compounds identified in the high throughput screen, CCG-63802 and CCG-63808, dose-dependently inhibit the TR-FRET signal between RGS4-AF488 and Tb- $G\alpha_o$  with  $IC_{50}$  values of 1.4 (0.76; 2.6  $\mu$ M) and 1.9  $\mu$ M (1.02; 3.5  $\mu$ M), respectively. D) The chemical structures of CCG-63802 and CCG-63808.  $n=3$  for all data. Data are presented as mean $\pm$ SEM or mean (95% CI) in B and C, respectively.

**Figure 2.** RGS specificity of A) CCG-63802 and B) CCG-63808 determined by multiplex FCPIA analysis ( $n\geq 3$ ). RGS coated beads were treated with the indicated concentration of compound for 15 minutes at room temperature, after which GDP/ $AlF_4^-$  bound  $G\alpha_o$ -AF532 was added and allowed to incubate with the RGS/compound mixture for 30 minutes prior to analysis. All data was calculated using nonlinear least squares regression with the bottom of the curves constrained to 0% binding. Data are presented as mean  $\pm$  SEM from 3 separate experiments.

**Figure 3.** Single Turnover GAP analysis of small molecule RGS inhibitors with RGS4. A) RGS4 treated with 100  $\mu$ M of CCG-4986, CCG-63808, or CCG-63802 lacks the ability to increase the intrinsic hydrolysis rate of  $G\alpha_o$ . Representative GAP data shown, however all experiments were performed a minimum of 3 times. B) Rate constants of GTP hydrolysis. Rate constants are

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presented as mean  $\pm$  SEM from at least 3 independent experiments. \*\* $p < 0.01$ , \*\*\* $p < 0.001$  vs. the DMSO treated RGS control.

**Figure 4.** CCG-63802 specifically binds to RGS4 and not to  $G\alpha_o$ . A) Purified RGS4 shows a dose dependent change in melting temperature in the presence of CCG-63802 ( $EC_{50} \sim 26 \mu\text{M}$ ). B) A saturating concentration of CCG-63802 ( $100\mu\text{M}$ ) does not affect the melting temperature of  $G\alpha_o$ . Data are presented as mean $\pm$ SEM of 3 separate experiments.

**Figure 5.** CCG-63802 and CCG-63808 are reversible inhibitors of A) RGS4 and B) RGS19. CCG-4986 is an irreversible inhibitor of RGS4 and RGS19. In all cases, RGS coated FCPIA beads were treated with  $50 \mu\text{M}$  of compound (or vehicle, DMSO) and then extensively washed. The beads were then split into two groups and tested for the ability to interact with  $G\alpha_o$ -AF532 in the presence or absence of  $50 \mu\text{M}$  Compound. Data shown are the mean $\pm$ SEM of three separate experiments.

**Figure 6.** CCG-63802 is less sensitive to glutathione than other RGS4 inhibitors. A) CCG-63802 and B) CCG-63808 retain full inhibitory activity in the presence of  $2 \text{ mM}$  glutathione, the potency is right shifted by approximately  $0.5\text{-}1 \text{ Log}$  (CCG-63802:  $\text{LogIC}_{50} -5.25\pm 0.07$  to  $-4.39\pm 0.07$ ; CCG-63808:  $\text{LogIC}_{50} -5.39\pm 0.06$  to  $-4.68\pm 0.03$ ). In contrast, C) CCG-4986 loses over two logs of potency ( $\text{LogIC}_{50} -5.87\pm 0.03$  to  $-3.66\pm 0.15$ ) in the presence of glutathione.  $n=2$ ;  $n=3$  for CCG-4986. Data presented as mean $\pm$ SEM.

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**Figure 7. CCG-63802 and CCG-63808 inhibit the GAP activity of a cysteine-null RGS4 mutant.** A) CCG-63802 or CCG-63808 (100  $\mu$ M) inhibits the ability of RGS4c to accelerate the rate of GTP hydrolysis by  $G\alpha_o$ . Representative data shown, however all experiments were performed a minimum of 3 times. B) Rate constants of GTP hydrolysis. Rate constants are presented as mean  $\pm$  SEM from at least 3 independent experiments. \*\* $p < 0.01$ , \*\*\* $p < 0.001$  vs. the DMSO treated RGS control.

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**Table 1.** RGS4/G $\alpha$ o TR-FRET high-throughput screening results. Actives were determined as follows: primary screen, >2SD from the negative control; TR-FRET Dose-response curve (DRC), IC<sub>50</sub> value <400  $\mu$ M; FCPIA DRC: IC<sub>50</sub> value <500  $\mu$ M.

<b>Assay</b>	<b>Compounds tested</b>	<b>Active*</b>	<b>Hit Rate (%)</b>
ChemDiv Library Subset	43878	162	0.37
TR-FRET DRC	114	11	0.025
FCPIA DRC	11	2	0.0046

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**Table 2.** RGS specificity of CCG-63802 and CCG-63808 determined by multiplex FCPIA analysis ( $n \geq 3$ ). All data was calculated from at least three independent experiments using nonlinear least squares regression with the bottom of the curves constrained to 0% binding. NI: No inhibition observed at highest concentration tested (100  $\mu\text{M}$ ).

RGS Protein	CCG-63802		CCG-63808	
	IC <sub>50</sub> ( $\mu\text{M}$ )	Hill Slope	IC <sub>50</sub> ( $\mu\text{M}$ )	Hill Slope
RGS4	9	-0.9	10	-1.4
RGS4c	>400	-0.4	>400	-0.8
RGS8	112	-0.6	74	-1.1
RGS16	42	-1.4	21	-2.1
RGS19	20	-0.6	46	-0.8
RGS7	NI	NI	NI	NI

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**Table 3.** RGS4 cysteine mutant sensitivity to CCG-63802. Data are presented as mean  $\pm$ SEM.

<b>RGS4 Mutant</b>	<b>IC<sub>50</sub> (<math>\mu</math>M)</b>	<b>pIC<sub>50</sub> Log(M)</b>	<b>Hill Slope</b>	<b>Inhibition (%) at 100<math>\mu</math>M</b>	<b>n</b>
WT	9	5.02 $\pm$ 0.07	-0.86 $\pm$ 0.11	87	9
C148A	43	4.37 $\pm$ 0.07	-0.95 $\pm$ 0.16	63	3
C132A	41	4.39 $\pm$ 0.07	-0.97 $\pm$ 0.18	66	3
C95A/C132A	32	4.50 $\pm$ 0.13	-0.78 $\pm$ 0.20	70	3
C148A/C132A	92	4.04 $\pm$ 0.07	-0.75 $\pm$ 0.11	57	3
C148A/C132A/C95A	~3000	2.55 $\pm$ 0.64	-0.33 $\pm$ 0.12	16	3
RGS4c	~8000	2.10 $\pm$ 1.50	-0.36 $\pm$ 0.30	13	6
A148C	~390	3.41 $\pm$ 0.17	-0.62 $\pm$ 0.14	30	3
A132C	174	3.76 $\pm$ 0.19	-0.80 $\pm$ 0.29	31	3
A95C	170	3.77 $\pm$ 0.23	-1.20 $\pm$ 0.82	30	3
A148C/A132C	33	4.47 $\pm$ 0.05	-1.48 $\pm$ 0.23	92	3
A148C/A95C	17	4.77 $\pm$ 0.12	-1.06 $\pm$ 0.28	100	3
A95C/A148C/A132C	16	4.79 $\pm$ 0.12	-0.63 $\pm$ 0.12	64	3

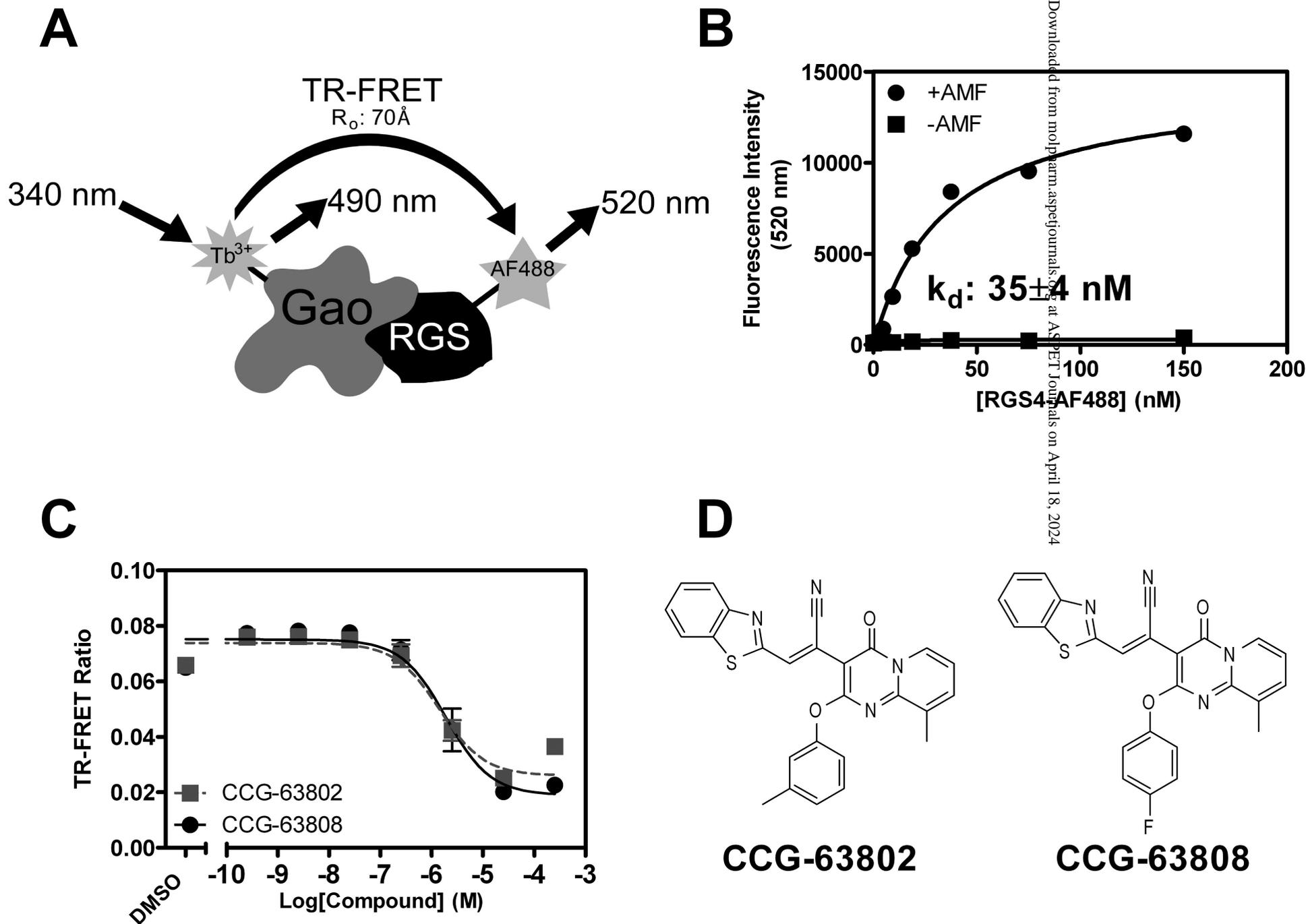


Figure 1.

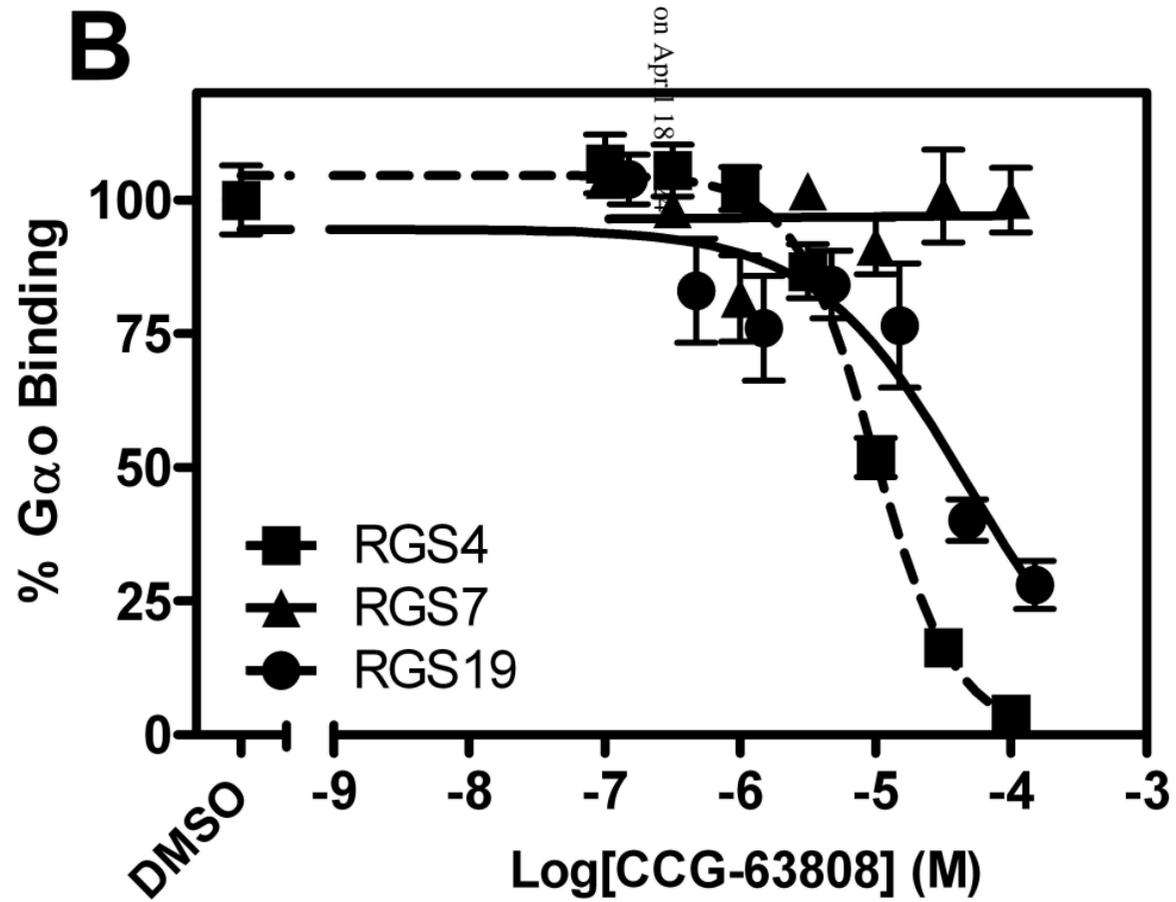
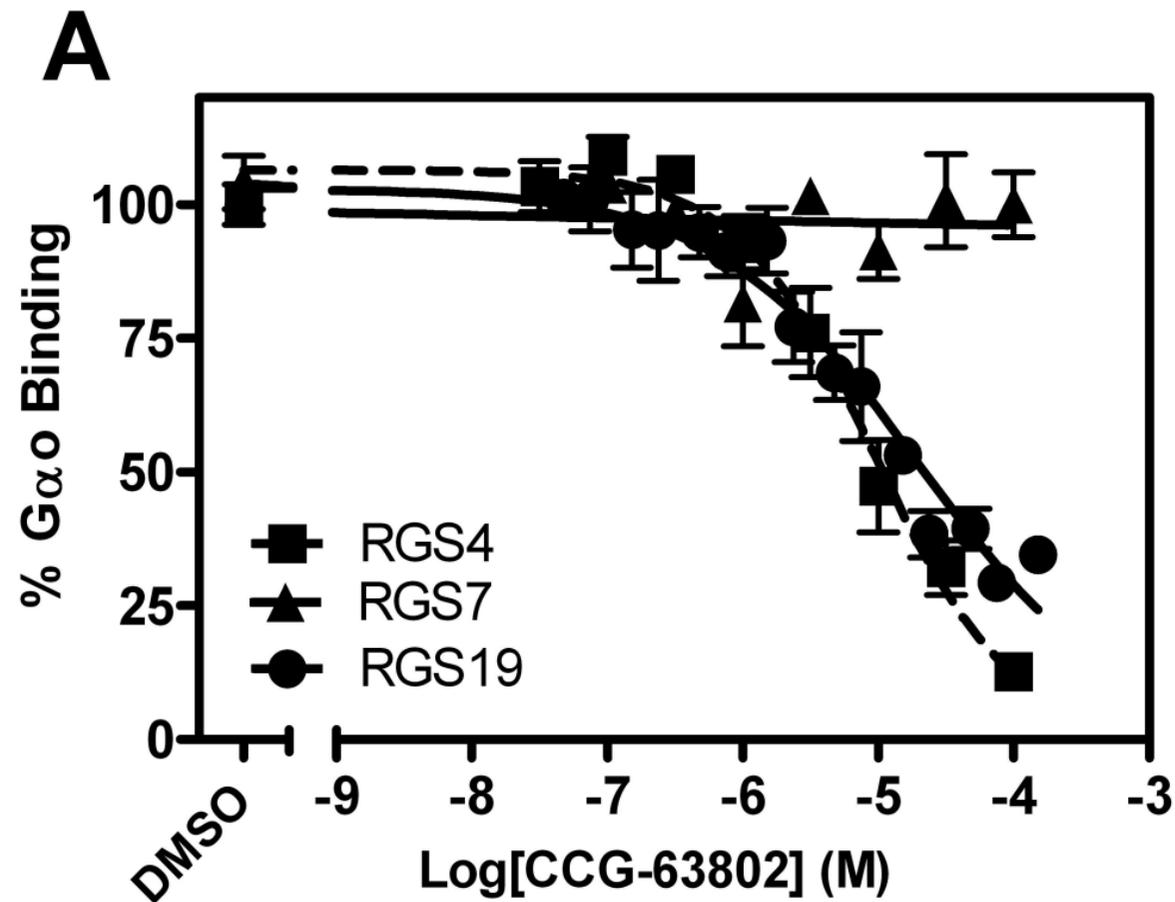


Figure 2.

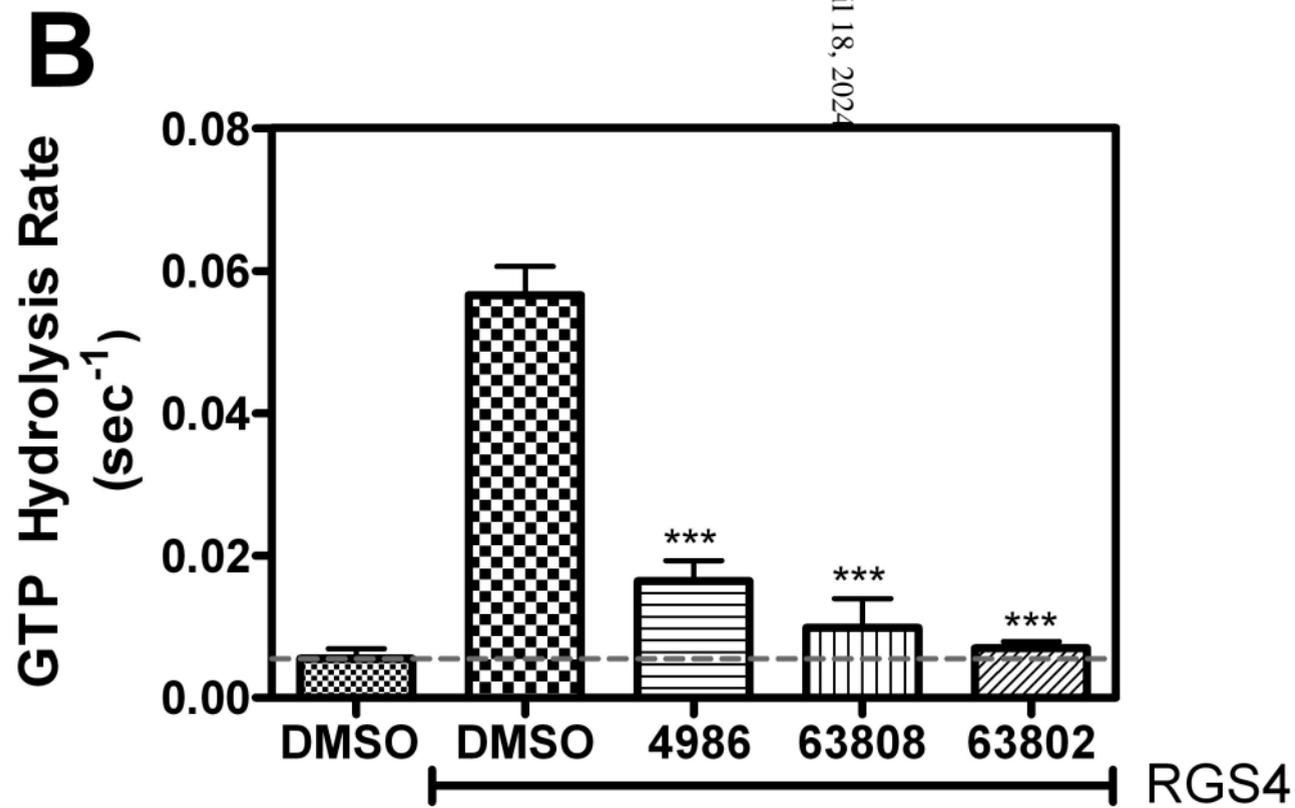
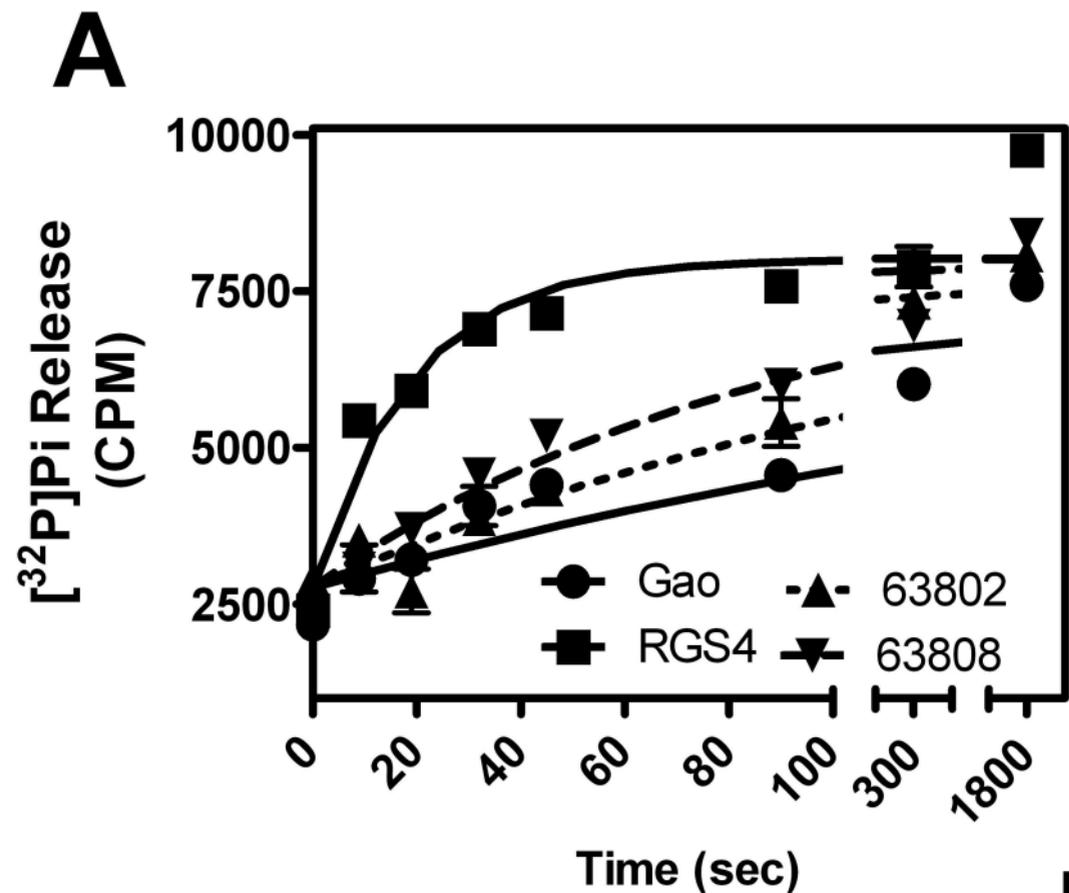
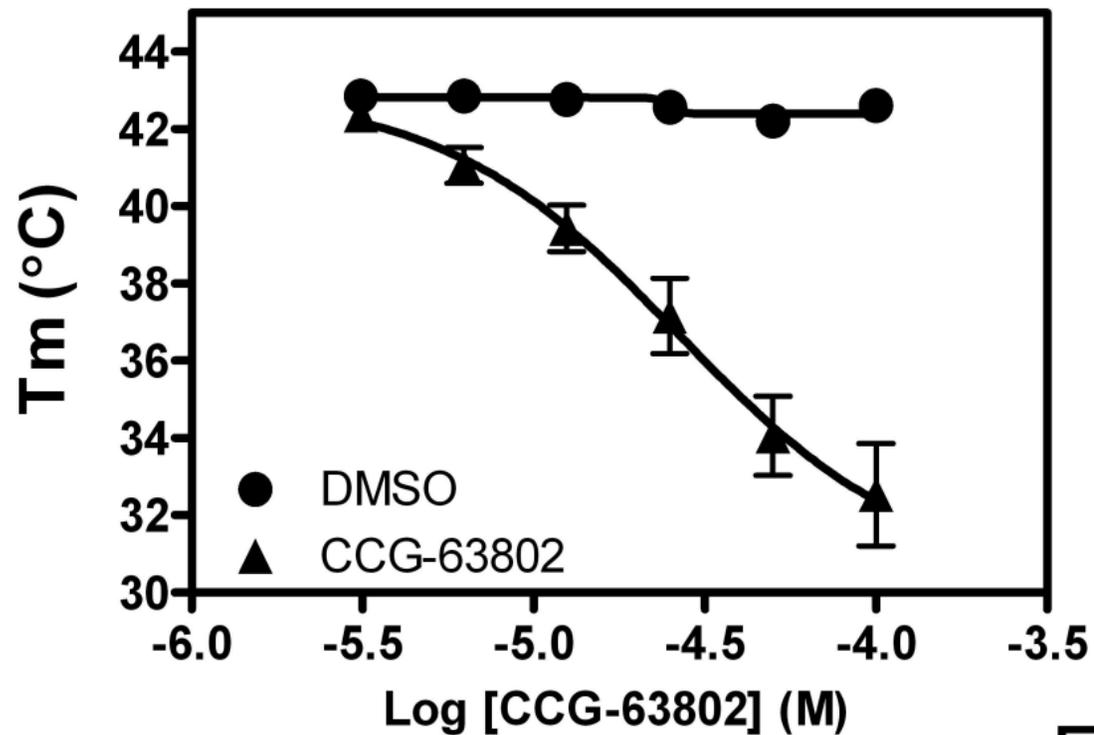
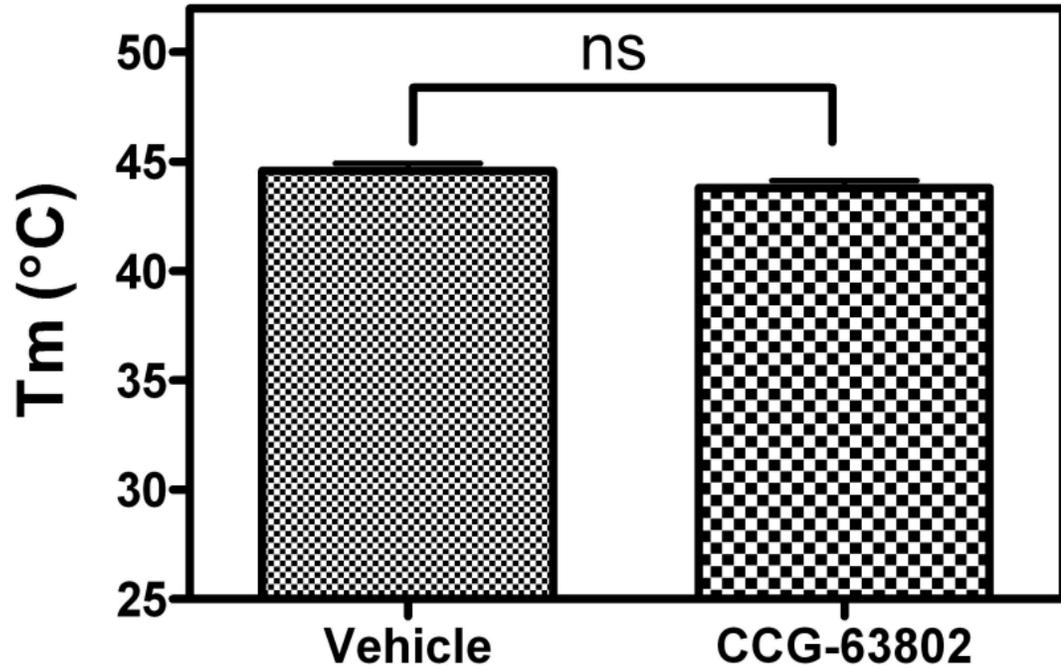


Figure 3.

**A****RGS4****B****G $\alpha$ o**

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Figure 4.

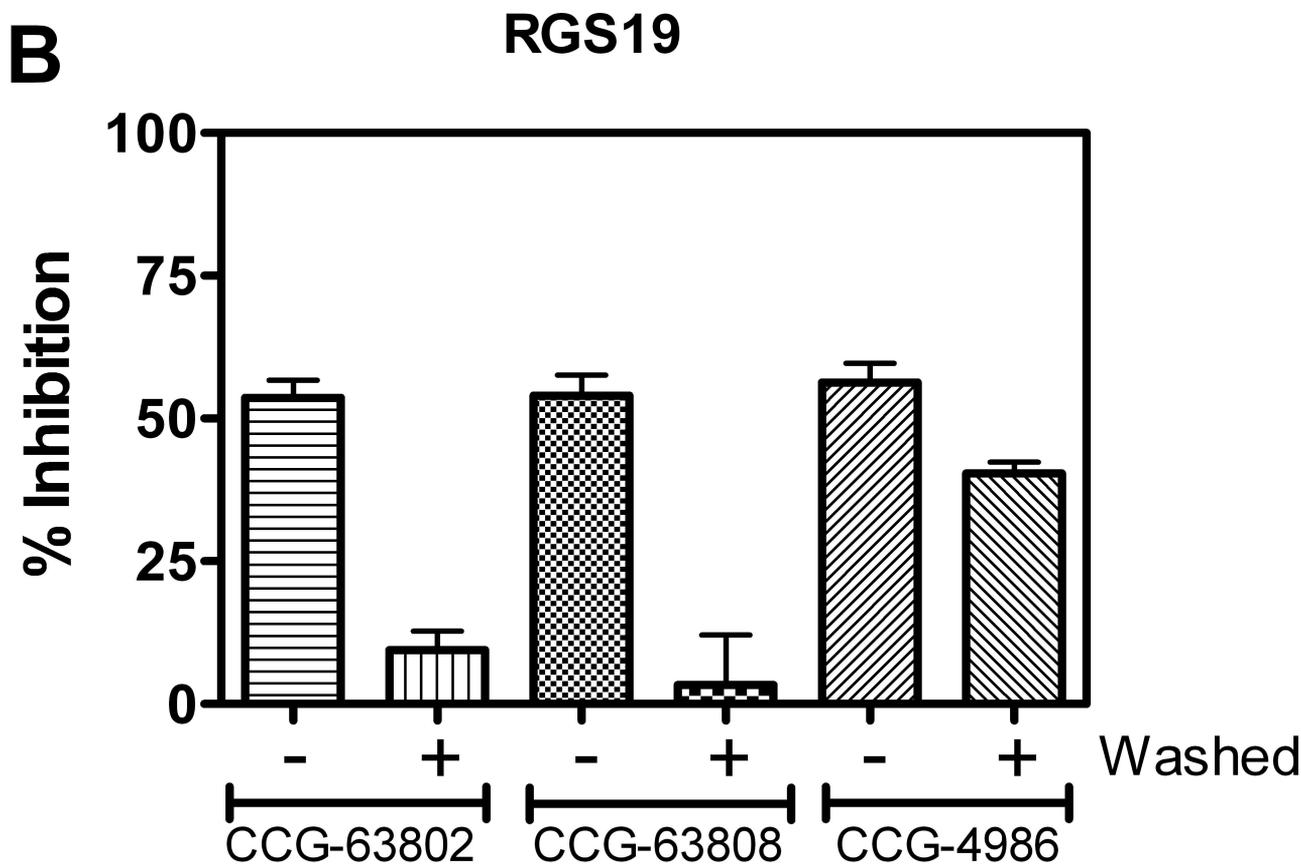
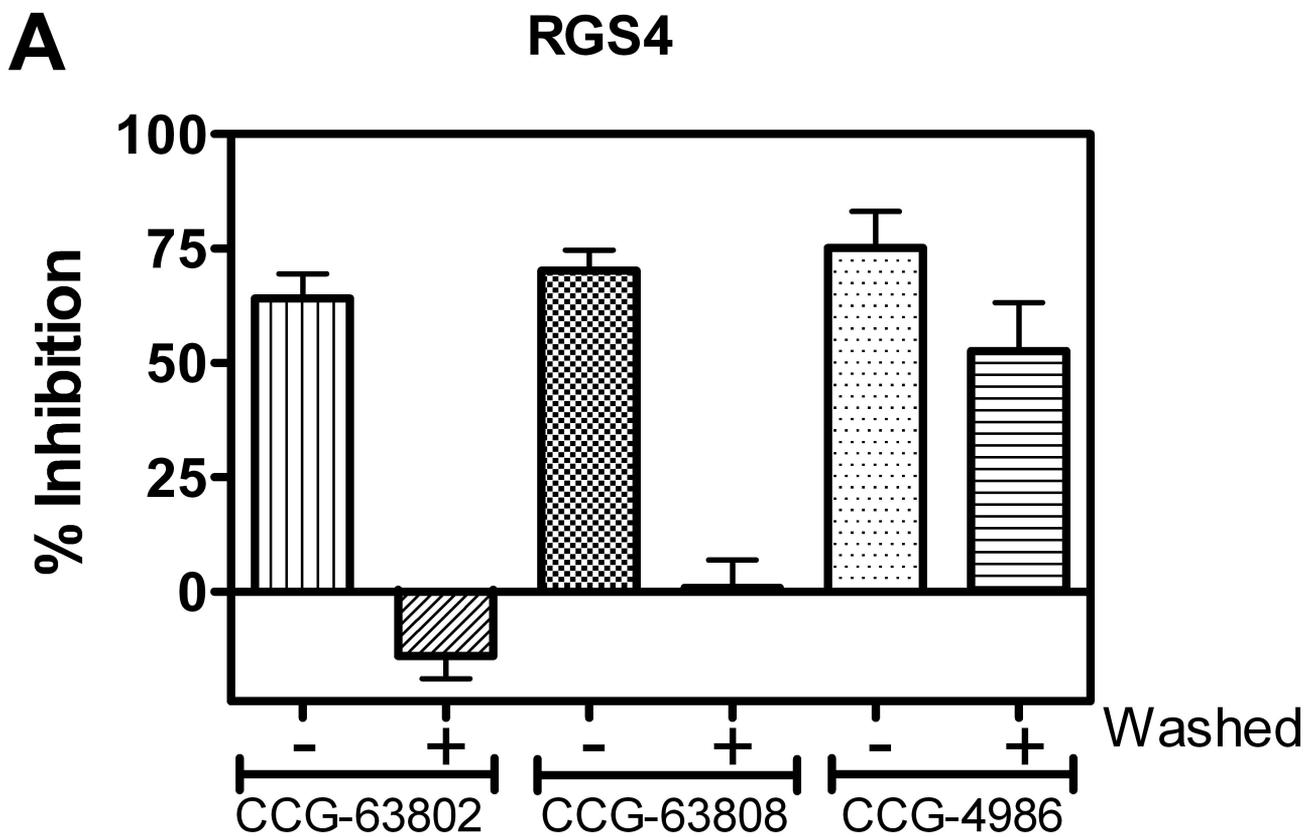
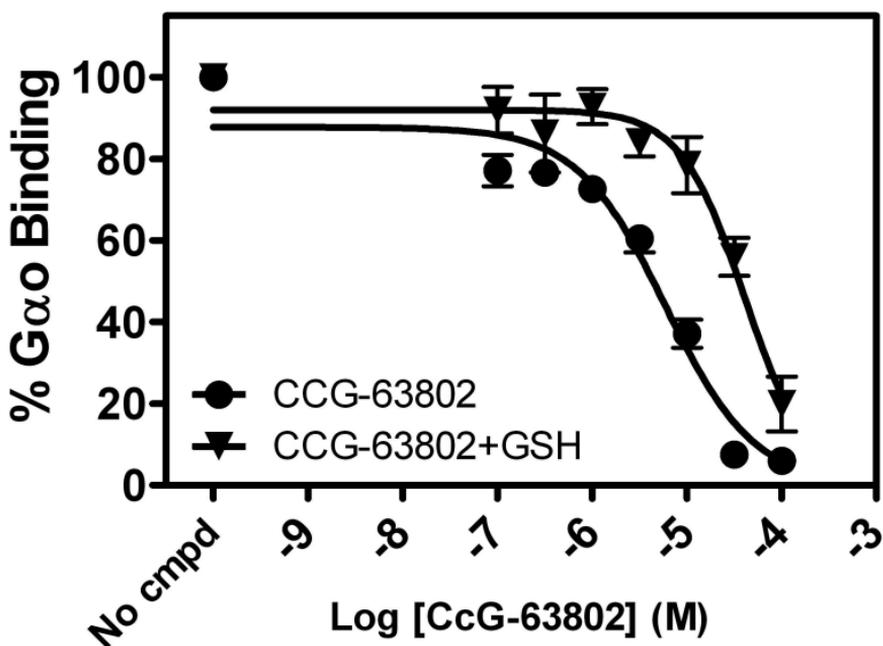
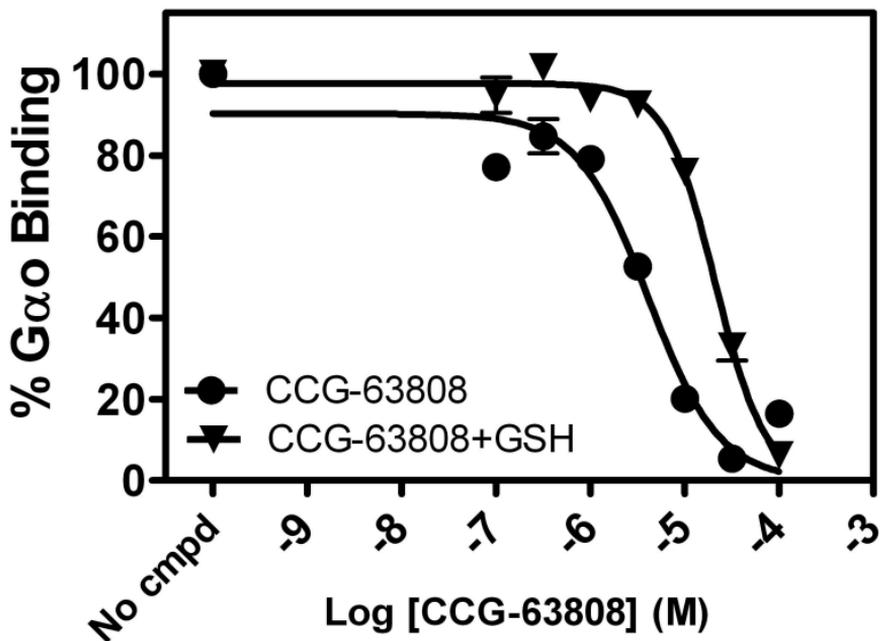
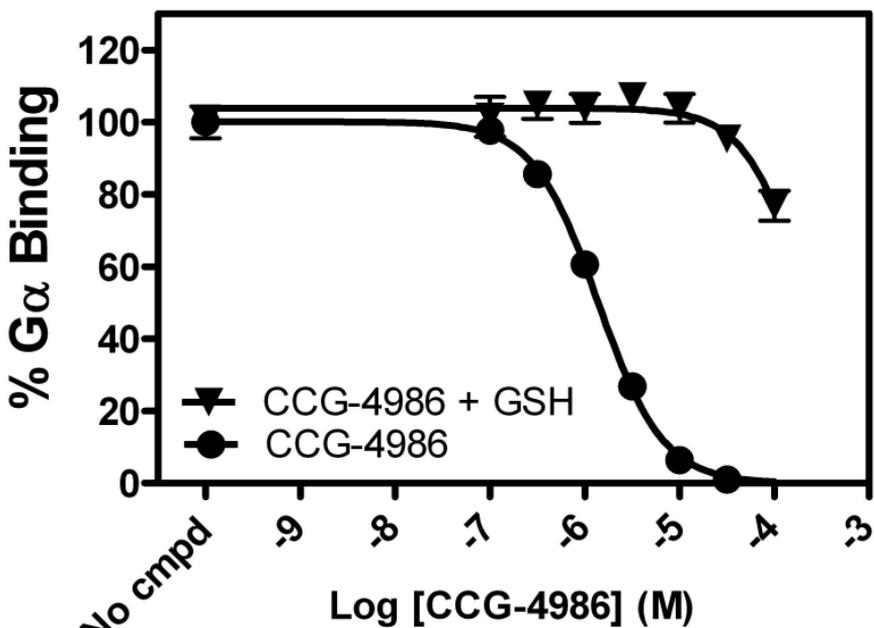


Figure 5.

**A****B****C****Figure 6.**

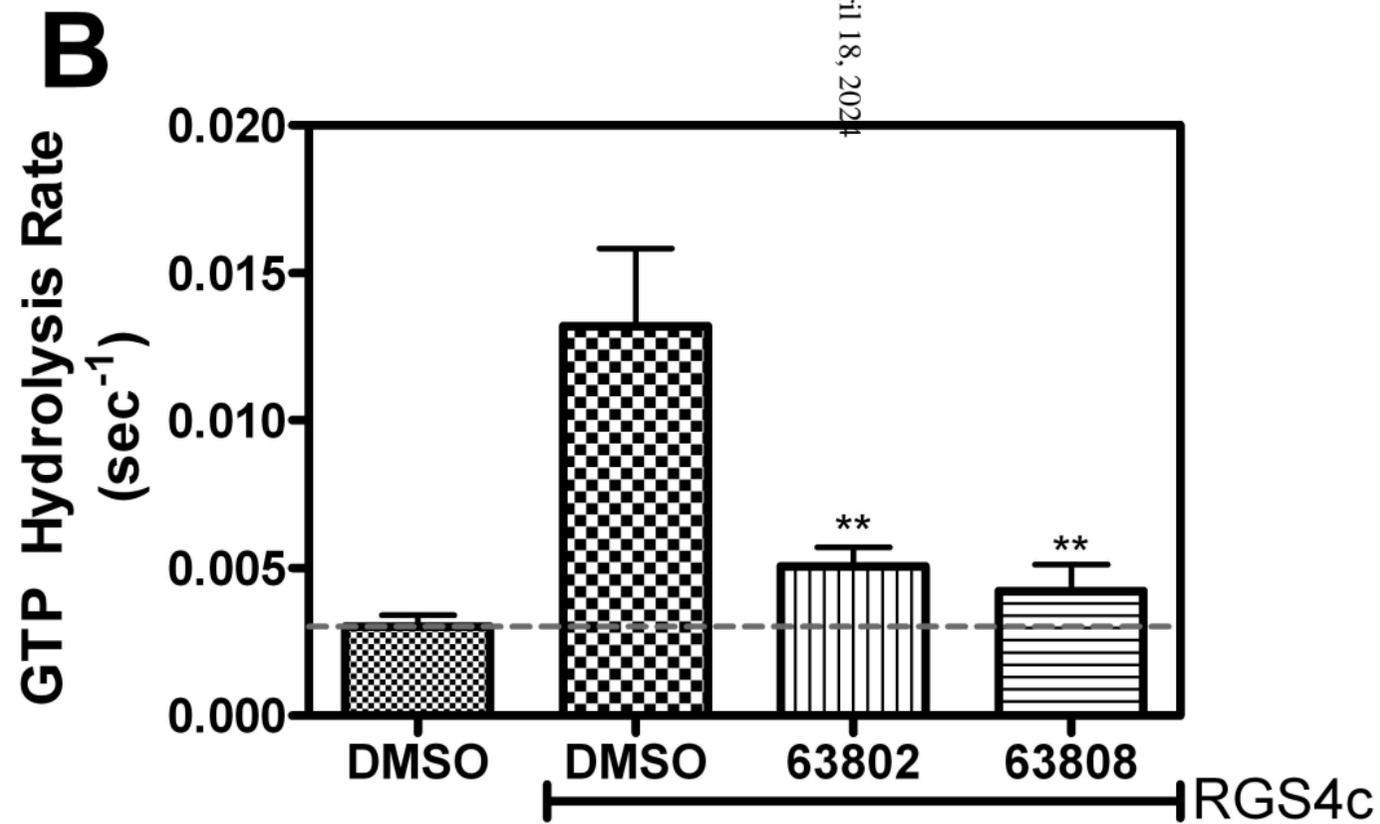
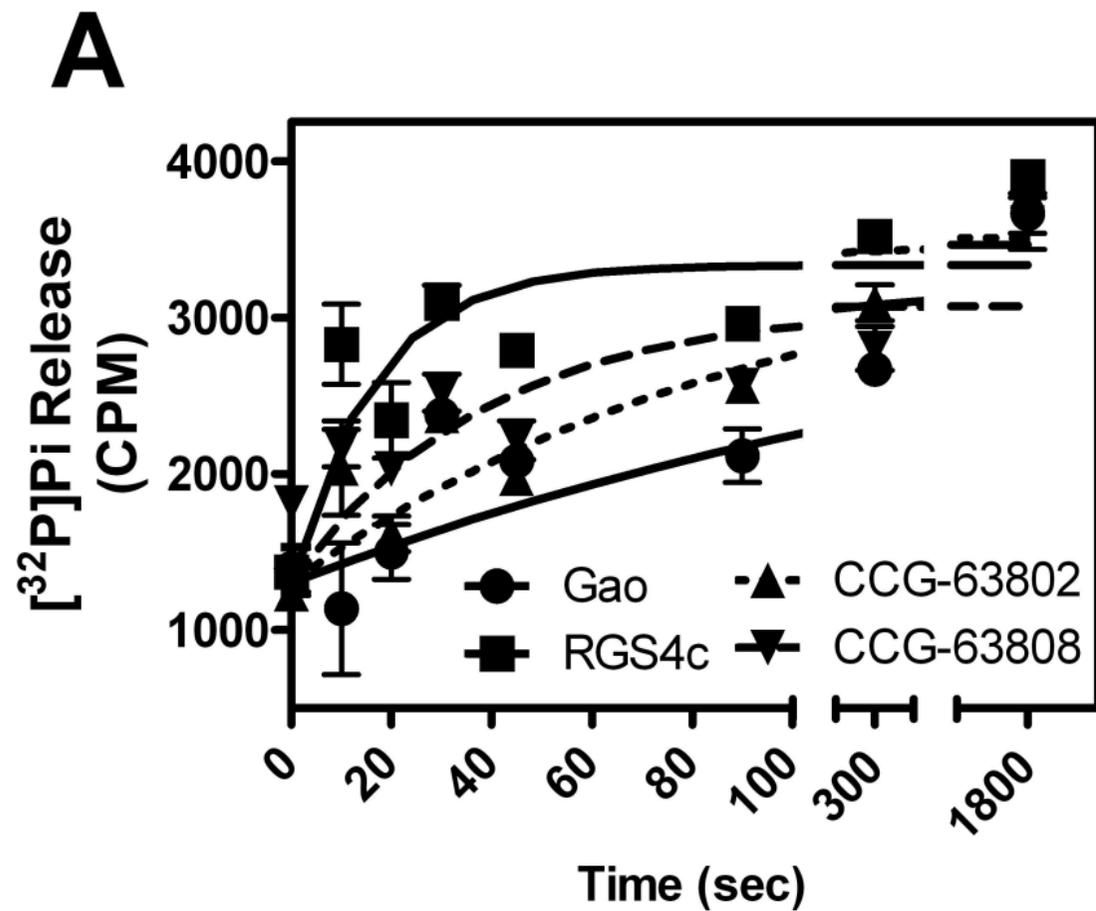


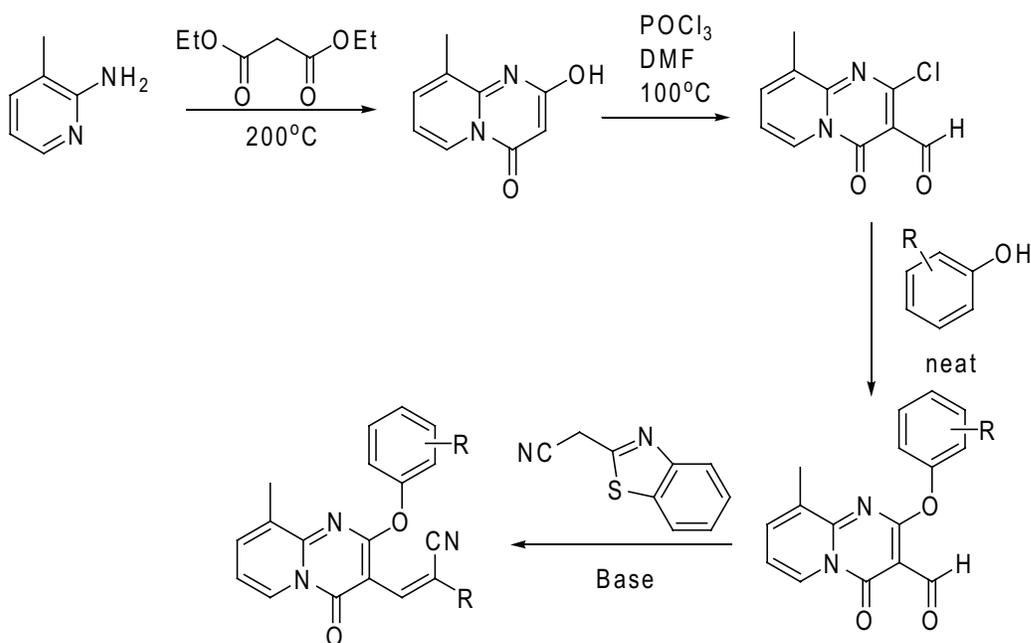
Figure 7.

## Supplemental Figures:

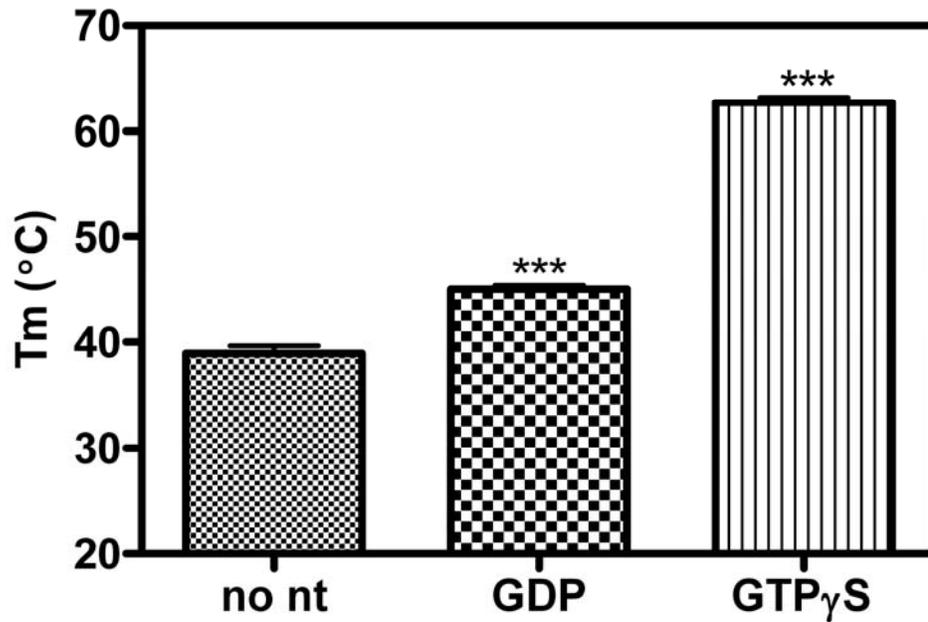
Blazer LL, Roman DL, Chung A, Larsen MJ, Greedy M, Husbands SM, Neubig RR.

Reversible, allosteric, small-molecule inhibitors of RGS proteins. Molecular

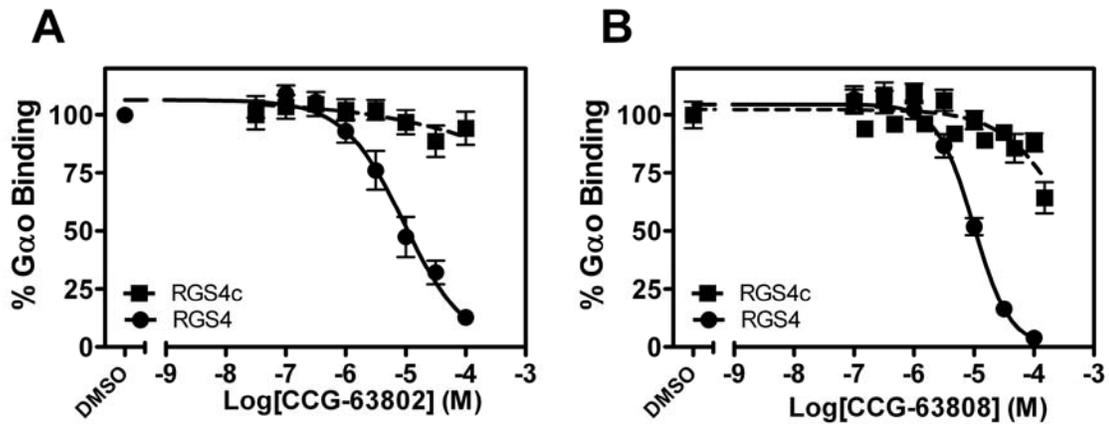
Pharmacology



**Supplemental Figure 1.** Reaction scheme for the synthesis of CCG-63802 and CCG-63808.



**Supplemental Figure 2.**  $G\alpha_o$  is thermally stabilized in presence of nucleotide. Purified  $G\alpha_o$  was stripped of nucleotide by gel filtration in a buffer containing EDTA. Lack of nucleotide was confirmed by spectroscopic analysis. The melting temperature ( $T_m$ ) of  $G\alpha_o$  (2.5  $\mu$ M) was determined by the thermal stability assay as described (see Methods) in the presence or absence of 50  $\mu$ M GDP or GTP $\gamma$ S. Nucleotide free (no nt)  $G\alpha_o$  has a  $T_m$  of  $38.9 \pm 0.7^\circ\text{C}$ . The protein is stabilized in the presence of 50  $\mu$ M GDP by 6°C ( $T_m$ :  $45.0 \pm 0.3^\circ\text{C}$ ) and is stabilized by 23°C in the presence of 50  $\mu$ M GTP $\gamma$ S ( $T_m$   $62.7 \pm 0.5^\circ\text{C}$ ). Data are presented as mean  $\pm$  SEM from 3 separate experiments.



**Supplemental Figure 3.** A) CCG-63802 and B) CCG-63808 are much less potent on a mutant form of RGS4 that lacks cysteine residues in the RH domain. Data are presented as mean  $\pm$  SEM from 3 separate FCPIA experiments.