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(54) **COMPOSITIONS AND METHODS FOR INHIBITING G PROTEIN SIGNALING**

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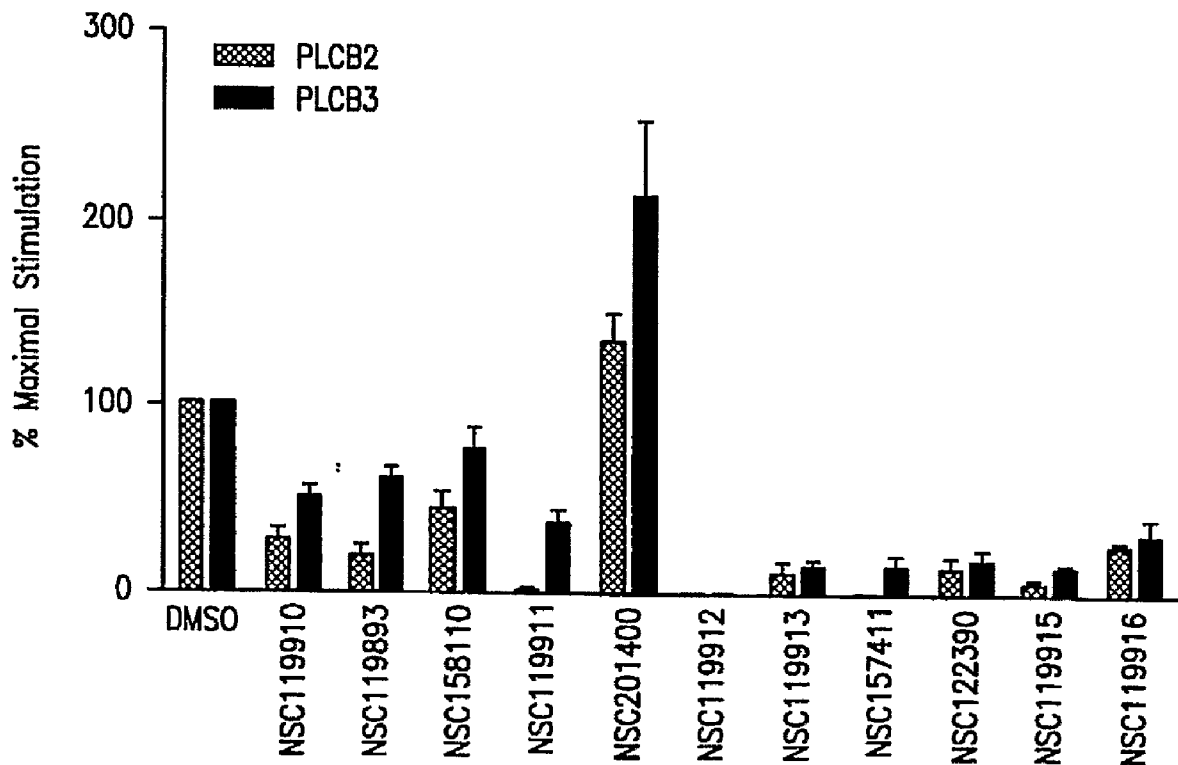
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(57) **ABSTRACT**

(21) Appl. No.: **11/885,981**

The present invention relates to methods for identifying agents which bind to specific amino acid residues of the protein interaction site of G protein  $\beta$  protein subunit. Compounds identified in accordance with the assay of the invention and methods for using the compound for modulating at least one activity of a G protein are also provide.

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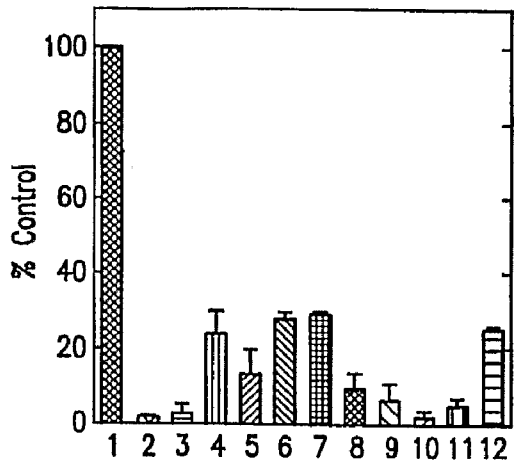


FIG. 1

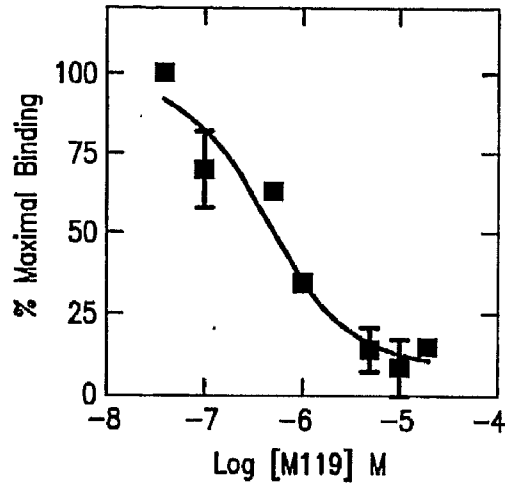


FIG. 2

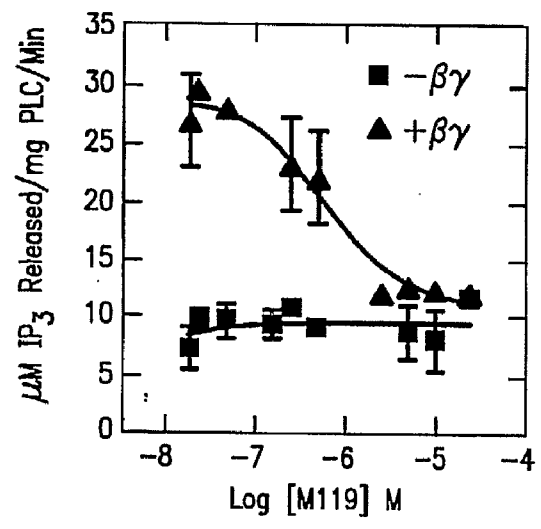


FIG. 3

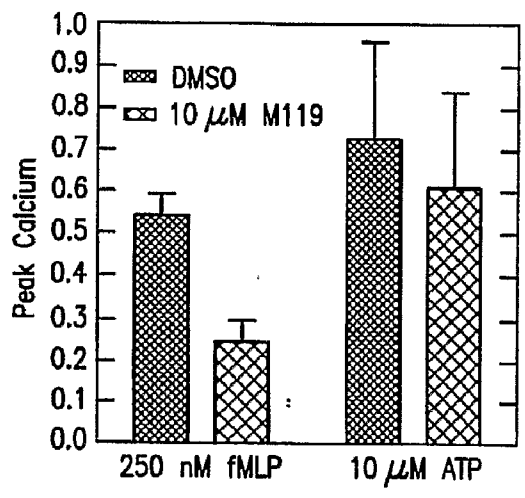


FIG. 4

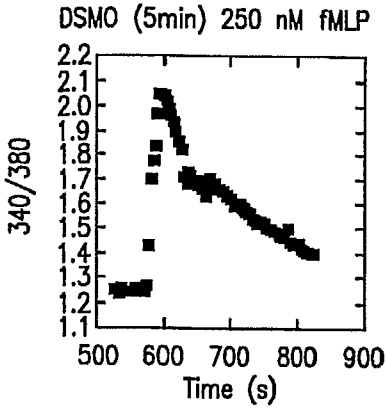


FIG. 5A

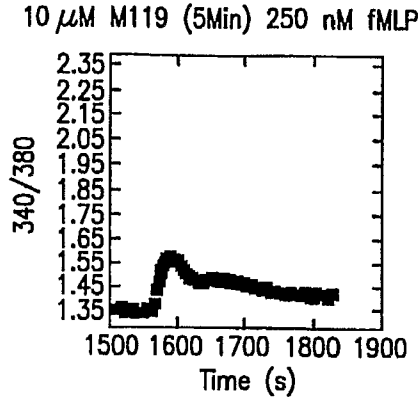


FIG. 5B

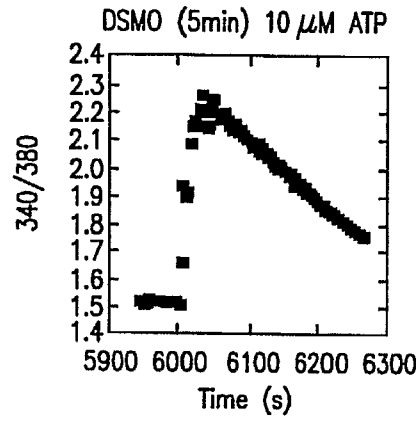


FIG. 5C

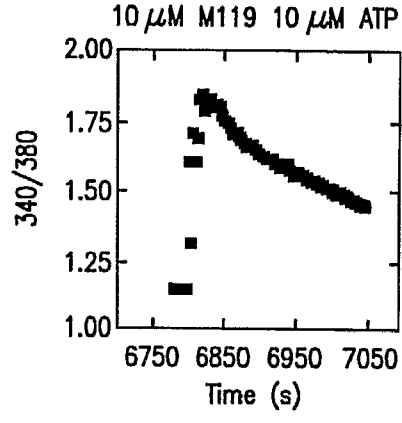


FIG. 5D

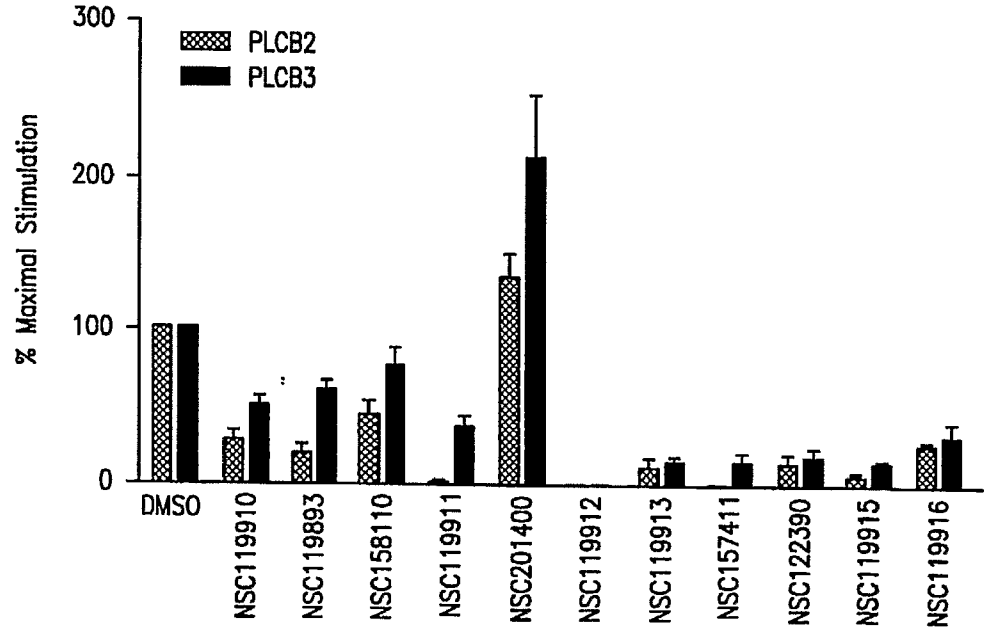


FIG. 6

## COMPOSITIONS AND METHODS FOR INHIBITING G PROTEIN SIGNALING

**[0001]** This invention was made in the course of research sponsored by the National Institutes of Health (Grant Nos. GM60286 and DK46371). The U.S. government may have certain rights in this invention.

### BACKGROUND OF THE INVENTION

**[0002]** Five mammalian isoforms of the G protein  $\beta$  subunit (37 kDa) and twelve isoforms of G protein  $\gamma$  (7.8 kDa) have been identified (Offermanns (2003) *Prog. Biophys. Mol. Biol.* 83:101-30). Obligate heterodimers composed of G protein  $\beta$  and  $\gamma$  subunits ( $G\beta\gamma$ ) function as regulatory molecules in various pathways in eukaryotic cells (Neves, et al. (2002) *Science* 296:1636-9; Clapham and Neer (1997) *Annu. Rev. Pharmacol. Toxicol.* 37:167-203). First characterized as a guanine nucleotide dissociation inhibitor (GDI),  $G\beta\gamma$  associates tightly with GDP-bound G protein  $\alpha$  subunits ( $G\alpha$ ) and thereby constitutes the basal form of the G protein heterotrimer in which neither  $G\alpha$  nor  $G\beta\gamma$  are active in signaling. Agonist-stimulated G protein coupled receptors (GPCRs) catalyze the exchange of GDP for GTP upon  $G\alpha$  and release of  $G\beta\gamma$  from the heterotrimer complex, liberating two active signaling species:  $G\alpha\cdot$ GTP and  $G\beta\gamma$ . Targets of  $G\beta\gamma$  signaling include the G protein-regulated inward-rectifying potassium channel (GIRK) (Krapivinsky, et al. (1993) *J. Biol. Chem.* 273:16946-52); type I, type II, and type IV isoforms of adenylyl cyclase (Tang and Gilman (1991) *Science* 254:1500-3; Sunahara, et al. (1996) *Annu. Rev. Pharmacol. Toxicol.* 36:461-80); mitogen-activated protein kinase (MAPK) (Schwindinger and Robishaw (2001) *Oncogene* 20:1653-60); phosphatidylinositol-3-kinase (PI3K) (Schwindinger and Robishaw (2001) supra); phospho-ducin (Schulz (2001) *Pharmacol Res* 43:1-10); at least two members of the G protein receptor kinase (GRK) family (Koch, et al. (1993) *J. Biol. Chem.* 268:8256-60; Inglese, et al. (1994) *Proc. Natl. Acad. Sci. USA* 91:3637-41); and other plextrin homology (PH) domain-containing proteins including the dynamin (Lin, et al. (1998) *Proc. Natl. Acad. Sci. USA* 95:5057-60; Scaife and Margolis (1997) *Cell Signal* 9:395-401) and the  $\beta 1$ ,  $\beta 2$ , and  $\beta 3$  isoforms of phospholipase C  $\beta$  (PLC  $\beta$ ) (Sternweis and Smrcka (1992) *Trends Biochem. Sci.* 17:502-6; Li, et al. (1998) *J. Biol. Chem.* 273:16265-72) and many others.

**[0003]**  $G\beta$  is a cone-shaped toroidal structure composed of seven four-stranded  $\beta$ -sheets arranged radially about a central axis (Wall, et al. (1995) *Cell* 83:1047-58; Lambright, et al. (1996) *Nature* 379:311-9). Each  $\beta$ -sheet is formed from elements of two consecutive WD-40 repeats, named for a conserved C-terminal Trp-Asp sequence in each repeat (Gettemans, et al. (2003) *Sci STKE* 2003:PE27). The  $G\gamma$  subunit, an extended helical molecule, is nested in a hydrophobic channel that runs across the base of the cone. The slightly narrower, "top" surface of the  $G\beta$  cone is the main binding site of  $G\alpha$  (through its switch II region) (Wall, et al. (1995) supra; Lambright, et al. (1996) supra), phospho-ducin (Loew, et al. (1998) *Structure* 6:1007-19; Gaudet, et al. (1996) *Cell* 87:577-88), and GRK2 (Lodowsky, et al. (2003) *Science* 300:1256-62), as shown by the crystal structures of these complexes. Mutational analysis indicates that many interaction partners of  $G\beta\gamma$ , including PLC  $\beta 2$  and adenylyl cyclase, bind to the same surface (Li, et al. (1998) supra; Ford, et al. (1998) *Science* 280:1271-4). Sites located along the sides of the  $G\beta$  torus serve as auxiliary binding surfaces that are specifically recognized by certain  $G\beta\gamma$  targets, exemplified in the crystal structures of  $G\alpha$  and phospho-ducin bound to  $G\beta\gamma$  (Wall, et al.

(1995) supra; Loew, et al. (1998) supra; Gaudet, et al. (1996) supra; Wall, et al. (1998) *Structure* 6:1169-83).

**[0004]** Phage display of randomized peptide libraries has been used to identify sequence requirements for binding and screen for peptide that bind to  $G\beta_1\gamma_2$  dimers (Scott, et al. (2001) *EMBO J.* 20:767-76). Although billions of individual clones were screened, most of the peptides that bound  $G\beta_1\gamma_2$  could be classified into four, unrelated groups based on amino acid sequence. One of these groups included a linear peptide (the "SIRK" peptide) with the sequence Ser-Ile-Arg-Lys-Ala-Leu-Asn-Ile-Leu-Gly-Tyr-Pro-Asp-Tyr-Asp (SEQ ID NO:1). The SIRK peptide inhibited PLC  $\beta 2$  activation by  $G\beta_1\gamma_2$  subunits with an  $IC_{50}$  of 5  $\mu$ M and blocked activation of PI3K. In contrast, the SIRK peptide had little or no effect on  $G\beta_1\gamma_2$  regulation of type I adenylyl cyclase or voltage-gated N-type  $Ca^{++}$  channel activity (Scott, et al. (2001) supra). This demonstrated that selective inhibition of  $G\beta\gamma$  binding partners could be achieved. Peptides belonging to all four groups competed with each other with a range of affinities for binding to  $G\beta_1\gamma_2$ , suggesting that all of the clones isolated from the phage display screen shared a common binding site on  $G\beta_1\gamma_2$  (Scott, et al. (2001) supra).

**[0005]** Subsequent experiments have shown that not only does the SIRK peptide block heterotrimer formation, but it also displaces  $G\alpha_{i1}$  from a  $G\beta_1\gamma_2\cdot G\alpha_{i1}$  complex in the absence of  $G\alpha_{i1}$  activation and activates G protein-dependent ERK1 and ERK2 pathways in intact cells (Ghosh, et al. (2003) *J. Biol. Chem.* 278:34747-50; Goubaeva, et al. (2003) *J. Biol. Chem.* 278:19634-41). In vitro experiments revealed that SIRK facilitated nucleotide exchange-independent heterotrimer dissociation (Goubaeva, et al. (2003) supra; Ghosh, et al. (2003) supra) potentially explaining the activation of ERK in intact cells. Other  $G\beta\gamma$  binding peptides such as QEHA, derived from adenylyl cyclase II (Weng, et al. (1996) *J. Biol. Chem.* 271:26445-26448; Chen, et al. (1997) *Proc. Natl. Acad. Sci. USA* 94:2711-2714) and amino acids 643-670 from the C-terminal region of PARK (GRK2) (Koch, et al. (1993) supra) could not promote dissociation of the heterotrimer, despite competing for  $G\alpha$  subunit binding (Ghosh, et al. (2003) supra). This indicates that competition for  $G\alpha$ - $G\beta\gamma$  subunit binding is not sufficient for these peptides to accelerate subunit dissociation.

**[0006]** Using a doping mutagenesis and rescreening strategy, a peptide similar to the SIRK peptide was derived that had higher affinity for  $G\beta_1\gamma_2$ . The sequence of this peptide is Ser-Ile-Gly-Lys-Ala-Phe-Lys-Ile-Leu-Gly-Tyr-Pro-Asp-Tyr-Asp (SEQ ID NO:2) (SIGK). In vitro studies with the SIGK peptide indicate that it too can displace  $G\alpha_{i1}$  from a heterotrimeric complex and also effectively prevents heterotrimer formation (Ghosh, et al. (2003) supra). The mechanism by which SIRK/SIGK mediates the dissociation of  $G\alpha_{i1}\cdot$ GDP from  $G\beta_1\gamma_2$  is not understood but was suggested to require a conformational change in  $G\beta_1\gamma_2$  subunits to account for the enhanced  $G\alpha_{i1}$  subunit dissociation rate in the presence of peptide (Ghosh, et al. (2003) supra).

### SUMMARY OF THE INVENTION

**[0007]** The present invention relates to a method for identifying an agent that modulates at least one activity of a G protein. This method involves contacting a G protein  $\beta$  subunit with a test agent and determining whether the agent interacts with at least one amino acid residue of the protein interaction site of the  $\beta$  subunit thereby identifying an agent that modulates at least one activity of the G protein.

**[0008]** The present invention also relates to a method for identifying an agent that binds at least one amino acid residue of the protein interaction site of the  $\beta$  subunit. The method

involves the steps of contacting a G protein  $\beta$  subunit with a test agent in the presence of a peptide that binds at least one amino acid residue of the protein interaction site of  $\beta$  subunit, and determining whether the agent inhibits the binding of the peptide to the at least one amino acid residue of the protein interaction site of the  $\beta$  subunit thereby identifying an agent that binds at least one amino acid residue of the protein interaction site of the  $\beta$  subunit.

**[0009]** The present invention further relates to a method for modulating at least one activity of a G protein. This method involves contacting a G protein with an effective amount of an agent that interacts with at least one amino acid residue of the protein interaction site of the G protein  $\beta$  subunit so that at least one activity of the G protein is modulated.

**[0010]** The present invention is also a method for preventing or treating a disease or condition involving at least one G protein  $\beta\gamma$  subunit activity. The method involves administering to a patient having or at risk of having a disease or condition involving at least one G protein  $\beta\gamma$  subunit activity an effective amount of an agent that interacts with at least one amino acid residue of the protein interaction site of the G protein  $\beta$  subunit so that the at least one activity of the G protein is modulated thereby preventing or treating the disease or condition involving the at least one G protein  $\beta\gamma$  subunit activity.

**[0011]** Diseases or conditions which involve G protein  $\beta\gamma$  subunit activities include heart failure, addiction, inflammation, and opioid tolerance.

**[0012]** A kit for identifying an agent that binds at least one amino acid residue of the protein interaction site of the  $\beta$  subunit is also provided. The kit of the invention contains a SIGK peptide or SIGK peptide derivative.

**[0013]** Agents identified in accordance with the screening methods of the present invention are further provided, wherein said agents have a structure of Formula I, II, or III.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**[0014]** FIG. 1 shows that small molecules predicted to bind to the G $\beta$  protein interaction site can interfere with peptide interactions at the protein interaction site. 1, control (DMSO); 2, NSC30820; 3, NSC12155; 4, NSC13984; 5, NSC117079; 6, NSC610930; 7, NSC293161; 8, NSC23128; 9, NSC402959; 10, NSC109268; 11, NSC125910; 12, SIGK in DMSO. 20  $\mu$ M of SIGK and 200  $\mu$ M of each small molecule were used in the assay.

**[0015]** FIG. 2 illustrates that NSC119910 binds to G $\beta\gamma$  and interferes with physiologically relevant protein interactions such as with the G $\alpha$  subunit.

**[0016]** FIG. 3 demonstrates the inhibition of phospholipase C-G $\beta\gamma$  interactions by NSC119910. Phospholipase enzymatic activity was determined using well-established methods (Ghosh and Smrcka (2003) *Meth. Mol. Biol.* 237:67-75).

**[0017]** FIG. 4 depicts the peak cytosolic Ca<sup>2+</sup> concentrations for neutrophils activated with fMLP or ATP agonists in the presence or absence of 10  $\mu$ M NSC119910. fMLP, n=3; ATP, n=2.

**[0018]** FIG. 5 shows representative experiments demonstrating peak cytosolic Ca<sup>2+</sup> concentrations, as well as the time taken for fluorescence intensity to decline to half-peak ( $t_{1/2}$ ) values, for neutrophils activated with fMLP or ATP in the absence and presence of 10  $\mu$ M NSC119910.

**[0019]** FIG. 6 shows inhibition of PLC- $\beta$ 2 and PLC- $\beta$ 3 activation in the presence of exemplary compounds of the instant invention.

#### DETAILED DESCRIPTION OF THE INVENTION

**[0020]** The protein interaction site for G proteins has now been appreciated. The structure of G $\beta\gamma$  bound to SIGK was

elucidated and indicates that SIGK binds to G $\beta\gamma$  as an  $\alpha$  helix across the G $\alpha$  interaction surface, in a position occupied by an  $\alpha$  helical region of the switch II domain of G $\alpha$  in the heterotrimer. The conformations of G $\beta\gamma$  in the presence and absence of SIGK are very similar. Thus, the crystal structure reveals how the peptide blocks G $\alpha$ -G $\beta\gamma$  interactions. The structure further indicates that G $\beta$  has evolved a highly reactive and specialized surface for interaction with diverse protein partners. This specialized surface is referred to herein as the "protein interaction site" or "protein interaction site of G $\beta$ ". Analysis of various characteristics of the protein interaction site led to the understanding that the basis for this surface as a preferred interaction surface is not an inherent conformational flexibility or unusually high surface accessibility of the site, but rather the prevalence of multiple types of potential interaction chemistries in this single binding surface. The specific amino acid combinations at this surface required for amino acid sequence recognition at the protein interaction site have also been determined. Moreover, the specific molecular interactions necessary for either acceleration of heterotrimer dissociation or inhibition of protein complex formation have been demonstrated.

**[0021]** Accordingly, the present invention relates to a method for identifying an agent that modulates (i.e., blocks or inhibits, or activates or potentiates) at least one activity of a G protein by contacting a G protein  $\beta$  subunit with a test agent (e.g., in a high-throughput screen) and determining whether the test agent interacts with at least one amino acid residue of the protein interaction site of the G protein  $\beta$  subunit. A G protein  $\beta$  subunit is intended to include any one of the five known mammalian G protein  $\beta$  subunit isoforms (Offermanns (2003) *supra*). An activity of a G protein is intended to mean the transduction of signals through the G protein to one or more downstream proteins including, but not limited to, G protein-regulated inward-rectifying potassium channel (GIRK); type I, type II, and type IV isoforms of adenylyl cyclase; mitogen-activated protein kinase (MAPK); phosphatidylinositol-3-kinase (PI3K); G protein receptor kinase (GRK) family members; and other plextrin/homology (PH) domain-containing proteins including the dynamins and the  $\beta$ 1,  $\beta$ 2, and  $\beta$ 3 isoforms of phospholipase C $\beta$  (PLC  $\beta$ ). Modulation of G protein activity occurs via binding of the agent to at least one amino acid residue of the protein interaction site thereby blocking interactions between the G $\beta\gamma$  subunits and G $\alpha$  subunit or the G $\beta\gamma$  subunits and the downstream proteins described herein.

**[0022]** The crystal structure of G $\beta\gamma$ <sub>1</sub> bound to SIGK revealed that the SIGK peptide interacts with residues of G $\beta$ <sub>1</sub> subunit that are utilized by several G $\beta\gamma$  binding proteins (e.g., downstream proteins). For example, Lys57, Tyr59, Trp99, Met101, Leu117, Tyr145, Met188, Asp246, and Trp332 of G $\beta$ <sub>1</sub> are involved in contacts with the GRK2 PH domain in the crystal structure of the G $\beta$ <sub>1</sub> $\gamma$ <sub>2</sub>•GRK2 complex, and all of these residues of G $\beta$ <sub>1</sub> are involved in SIGK contacts as well (Table 1). This is in spite of the fact that the secondary structures of the PH domain that contact G $\beta$ <sub>1</sub> (the RH-PH loop, the  $\alpha$ CT region, and  $\beta$ 4 strand) are completely dissimilar to the purely helical SIGK peptide (Lodowski, et al. (2003) *supra*). This theme is recapitulated in the complex of G $\beta$ <sub>1</sub> with phosphoducin (Ford, et al. (1998) *supra*) where a common subset of G $\beta$ <sub>1</sub> residues contacts a binding partner with different secondary structure from GRK2. Notably, the switch II region of G $\alpha$ <sub>1</sub> forms an  $\alpha$ -helix that is bound in almost the same orientation as the SIGK peptide. However, switch II of G $\alpha$ <sub>1</sub> has no

sequence similarity to the SIGK peptide, although it contains a lysine (Lys210) which is oriented in almost the same position as Lys4 of SIGK (Goubaeva, et al. (2003) supra).

TABLE 1

G $\alpha_{i1}$	Phosducin	GRK2	SIGK	PLC $\beta$	AC	GIRK	Ca <sup>++</sup>
	42						
	44						
	46						
	47						
52							
53							
55		55			55	55	55
<u>57</u>	<u>57</u>	<u>57</u>	<u>Lys57</u>		<u>57</u>		<u>57</u>
<u>59</u>	<u>59</u>	<u>59</u>	<u>Tyr59</u>			<u>59</u>	
75	75	75					
		76					
78		78			78	78	78
80				80		80	
88							
89				89	89	89	
90							
91							
92							
		95					
		96					
	98	98					
<u>99</u>	<u>99</u>	<u>99</u>	<u>Trp99</u>	<u>99</u>	<u>99</u>	<u>99</u>	
			<u>Val100</u>				
<u>101</u>	<u>101</u>	<u>101</u>	<u>Met101</u>	<u>101</u>	<u>101</u>		<u>101</u>
<u>117</u>	<u>117</u>	<u>117</u>	<u>Leu117</u>	<u>117</u>	<u>117</u>		<u>117</u>
119				119	119		119
132							
143				143			143
144							
<u>145</u>	<u>145</u>	<u>145</u>	<u>Tyr145</u>				
	162						
182							
<u>186</u>	<u>186</u>		<u>Asp186</u>	<u>186</u>	<u>186</u>		<u>186</u>
<u>188</u>	<u>188</u>	<u>188</u>	<u>Met188</u>				
204	204	204					
<u>228</u>	<u>223</u>		<u>Asp228</u>	<u>228</u>	<u>228</u>	<u>228</u>	<u>228</u>
<u>230</u>	<u>230</u>		<u>Asn230</u>				
<u>246</u>	<u>246</u>	<u>246</u>	<u>Asp246</u>	<u>246</u>	<u>246</u>		
	274						
	290	290					
	292						
	304						
	310						
	311						
	314	314					
<u>332</u>	<u>332</u>	<u>332</u>	<u>Trp332</u>	332	332		332
41%	44%	44%	—	54%	67%	43%	60%

Key to column headings:

G $\alpha_{i1}$ , the crystal structure of the G $\alpha_{i1}$ •G $\beta_1\gamma_2$  heterotrimer (Wall, et al. (1995) supra; Wall, et al. (1998) supra);  
 phosducin, the phosducin•G $\beta_1\gamma_2$  complex (Gaudet, et al. (1996) supra);  
 GRK2, the GRK2•G $\beta_1\gamma_2$  complex (Lodowski, et al. (2003) supra);  
 SIGK, the SIGK•G $\beta_1\gamma_2$  complex;  
 PLC  $\beta$ , mutational analysis of the PLC  $\beta_2/3$ •G $\beta_1\gamma_2$  complexes (Li, et al. (1998) supra; Ford, et al. (1998) supra);  
 AC, mutational analysis of the adenylyl cyclase type I/II•G $\beta_1\gamma_2$  complex (Ford, et al. (1998) supra);  
 GIRK, mutational analysis of G $\beta_1\gamma_2$  interaction with the GIRK1/4 channels (Ford, et al. (1998) supra);  
 Ca<sup>++</sup>, mutational analysis of G $\beta_1\gamma_2$  interaction with N or P/Q type calcium channels (Ford, et al. (1998) supra; Agler, et al. (2003) J. Gen. Physiol. 121: 495-510).

Underlined residues indicate residues important for the SIGK•G $\beta_1\gamma_2$  interaction.

The last row indicates the percentage of residues that are shared between the target and the SIGK interfaces.

**[0023]** When mutational data for G $\beta\gamma$  targets PLC  $\beta_2$ , adenylyl cyclase, and GIRK and CC $\alpha$ 1B calcium channels are included in this analysis, the footprint of SIGK upon G $\beta$  is similar to the footprints of these former targets (Li, et al.

(1998) supra; Ford, et al. (1998) supra). Of the thirteen residues from G $\beta$  that encompass the protein interaction site, nine (Lys57, Tyr59, Trp99, Met101, Leu117, Tyr145, Met188, Asp246, and Trp332) are also found as contacting residues in the G $\alpha$ , PI3K, and phosducin complexes (Table 1). These residues reflect a consensus set of residues utilized by many G $\beta$  binding partners. An additional three of the thirteen residues (Asp186, Asp228, and Asn230) are shared amongst SIGK and two of the other protein complex structures. One of the thirteen, Val100, contacts SIGK through its main chain oxygen and is not involved in binding interactions in the other complexes. The SIGK binding residues that are most sensitive to mutational perturbation are also the most frequently involved in interactions with other G $\beta$  binding partners. SIGK was identified from a random peptide phage display where multiple peptides, unrelated by sequence, appeared to bind to a common protein interaction site on G $\beta_1$ .

**[0024]** Because of the extensive overlap between the residues of G $\beta_1$  that are accessed by SIGK and those involved in the binding of protein G $\beta\gamma$  targets, SIGK is a competitive inhibitor of multiple G $\beta\gamma$  binding reactions. The closely related SIRK peptide has effects on several G $\beta\gamma$ -dependent pathways; it blocks G $\beta\gamma$ -mediated activation of PLC  $\beta_2$ , PLC  $\beta_3$  and PI3K in enzyme assays, and induces ERK I/II activation in a cell-based assay (Scott, et al. (2001) supra; Goubaeva, et al. (2003) supra). These effects are sensitive to mutations of residues in SIGK that interact with the surface of G $\beta$ , as Lys4, Ala5, Phe6, Ile8, Leu9, and Gly10 of SIGK have all been shown by alanine scanning to be important for inhibition of PLC  $\beta_2$  activation by G $\beta_1\gamma_2$  (Scott, et al. (2001) supra). In addition, Leu9 of SIGK is important for the ability of SIGK to activate MAPK pathways in cell culture (Goubaeva, et al. (2003) supra). However, SIRK does not block inhibition of adenylyl cyclase type I or N-type Ca<sup>2+</sup> channel regulation, even though their footprints are quite similar to those of G $\alpha$  and PLC  $\beta_2$  (Scott, et al. (2001) supra). Conversely, mutations in GP that abrogate SIGK binding do not equally affect interaction with other G $\beta\gamma$  binding partners. For example, mutation of Leu117 to alanine decreases the ability of G $\beta_1\gamma_2$  to activate adenylyl cyclase type II and PLC  $\beta_3$  and to bind GRK2 and SIGK, but has no effect on GIRK1/GIRK4 potassium channel activation, CC $\alpha$ 1B calcium channel activation, or PLC  $\beta_2$  activation (Table 1) (Li, et al. (1998) supra; Ford, et al. (1998) supra). Similarly, mutation of Trp332 of G $\beta_1\gamma_2$  to alanine reduces affinity of G $\beta_1\gamma_2$  for SIGK and impairs stimulatory activity towards adenylyl cyclase type II, CC $\alpha$ 1B and both PLC  $\beta_2$  and PLC  $\beta_3$ , but does not affect interaction with GRK2, activation of GIRK1/GIRK4, or inhibition of adenylyl cyclase type I (Li, et al. (1998) supra; Ford, et al. (1998) supra). Both Leu117 and Trp332 of G $\beta_1\gamma_2$  form part of the G $\alpha_i$  and G $\alpha_{i1}$  binding sites of G $\beta_1$  (Wall, et al. (1995) supra; Lambright, et al. (1996) supra; Wall, et al. (1998) supra) and mutation of Leu117 also affects G $\alpha_{i1}$  association with G $\beta_1\gamma_2$  (Li, et al. (1998) supra; Ford, et al. (1998) supra).

**[0025]** Unlike other peptides that block heterotrimer formation (Ghosh, et al. (2003) supra), SIGK promotes nucleotide exchange-independent dissociation of G $\beta_1\gamma_2$  from G $\alpha_{i1}$  (Ghosh, et al. (2003) supra; Goubaeva, et al. (2003) supra). For example, a peptide derived from the C-terminus of GRK2 blocks heterotrimer formation (Ghosh, et al. (2003) supra) but does not promote G $\alpha_{i1}$ •G $\beta_1\gamma_2$  subunit dissociation, even though the structure of the GRK2•G $\beta_1\gamma_2$  complex indicates that this peptide should utilize much the same surface of G $\beta_1$

as SIGK (Lodowski, et al. (2003) supra). Not to be bound by theory, SIGK could promote heterotrimer dissociation by either of two mechanisms. SIGK may induce conformational changes on  $G\beta_1$  that propagate beyond the SIGK binding site and disrupt other interactions between  $G\beta_1$  and  $G\alpha_{t1}$ . However, the  $G\beta_1\gamma_2$ \*SIGK structure shows that SIGK does not induce substantial conformational change in  $G\beta_1$  outside of the SIGK binding site itself. The second mechanism relies on the assumption that  $G\alpha_{t1}$  can dynamically detach from and rebound to either of two surfaces on  $G\beta$ : the switch II interaction site on the top face of  $G\beta_1$ , where SIGK binds in a similar orientation, and the N-terminal interaction surface on blade one of  $G\beta_1$ . Transient release from  $G\alpha_{t1}$  at the switch II interface would allow SIGK access to  $G\beta_1$ . Complete release of  $G\alpha_{t1}$  from  $G\beta$  could then occur if the off-rate for SIGK is slower than that for dissociation of the N-terminus of  $G\alpha_{t1}$ . Thus the GRK2 peptide, which binds the top surface of  $G\beta$ , may dissociate too quickly to promote dissociation of  $G\alpha$ . This dynamic model of  $G\beta\gamma$  interactions is biologically relevant, since many  $G\beta\gamma$  binding targets exhibit binding outside of the top surface of  $G\beta$  and may also transiently sample alternate surfaces on  $G\beta$ .

**[0026]** The ability of the protein interaction site of  $G\beta_1\gamma_2$  to recognize a range of protein ligands with diverse secondary structures indicates that it may be an example of a preferential protein binding site (see, e.g., DeLano, et al. (2000) *Science* 287:1279-1283). Preferential binding surfaces are characterized as having high solvent accessibility, low polarity, and a large degree of conformational flexibility (Scott, et al. (2001) supra; Ma, et al. (2001) *Curr. Opin. Struct. Biol.* 11:364-9; Bogan and Thorn (1998) *J. Mol. Biol.* 280:1-9; Clackson and Wells (1995) *Science* 267:383-6; DeLano (2002) *Curr. Opin. Struct. Biol.* 12:14-20). Moreover, preferential binding sites are likely to contain an unusually high concentration of so-called "hot spots", i.e., residues that, if mutated to alanine, reduce binding energy at least ten-fold (DeLano (2002) supra). Hot spots have been described for both protein-protein and protein-small molecule interfaces; often point mutations to any hot spot on a surface completely abrogate complex formation, even when the binding interfaces bury several hundred  $\text{\AA}^2$  of total surface area (Bogan and Thorn (1998) supra; Clackson and Wells (1995) supra; Thanos, et al. (2003) *J. Am. Chem. Soc.* 125:15280-1; Zhang, et al. (2003) *J. Biol. Chem.* 278:33097-104). These criteria have been used herein to evaluate the protein interaction site of  $G\beta_1$  as a protein surface that is predisposed by its chemical composition and surface properties to serve as a protein binding site. Of the twelve residues in the protein interaction site of  $G\beta$ , eight (Lys57, Tyr59, Leu117, Tyr145, Asp186, Met188, Asn230, and Trp332) met the energetic criterion for a hot spot residue. Replacement of any of these residues by alanine resulted in a 10-fold reduction in the affinity of  $G\beta_1\gamma_2$  for SIGK. It is clear that all of these residues act as energetically important nodes that contribute favorably to SIGK binding. The SIGK binding surface of  $G\beta_1$  contains several residues that have been shown to be enriched in hot spots (Bogan and Thorn (1998) supra). These include tyrosine, tryptophan and arginine; bulky residues that are capable of forming both polar and non-polar interactions. The protein interaction site of  $G\beta$  is significantly more populated with aromatic residues than the rest of the  $G\beta$  surface. 38% of the SIGK binding surface versus 8.5% of the total non-glycine surface accessible  $G\beta$  residues is composed of Phe, Tyr, His, or Trp. Therefore, the protein interaction site of  $G\beta$  is more nonpolar; in total, 62% of the protein interac-

tion site of  $G\beta$  is nonpolar compared to 29% of  $G\beta$  surface accessible residues. Further, asparagine and aspartic acid, which have a moderately favorable distribution among hot spot surfaces, account for four of the thirteen residues in the protein interaction site of  $G\beta$ . This combination of aromatic and charged residues allows for accommodation of binding partners with diverse chemical properties at the  $G\beta$  protein interaction site. Preferential binding surfaces are expected to have high surface accessibility (DeLano, et al. (2000) supra). To analyze this property of the protein interaction site of  $G\beta$ , the total surface accessible area was calculated for the  $G\beta$  molecule on a residue, main chain, and side chain basis. Most amino acids in the protein interaction site of  $G\beta$  were not significantly more accessible than others of their type in  $G\beta$ . However, five residues showed significant deviation from the mean: Tyr59, Trp99, Met101, Leu117, and Trp332. In the case of Trp99, side chain surface accessibility was significantly greater than the type average; the main chain of Tyr59, Trp99, and Met101 were more accessible than the mean. Leu117 had significantly higher main chain and side chain accessibility than the mean.

**[0027]** Conformational flexibility or adaptability has been cited as an important determinant of a preferential binding surface, since such surfaces are better able to bind to structurally unrelated protein targets (DeLano, et al. (2000) supra). Residue flexibility can be quantified in terms of relative positional variation in the context of several protein complexes. Histogram analysis of the RMSD relative to uncomplexed  $G\beta_1\gamma_1$  of all  $G\beta$  residues in four crystal structures ( $G\beta_1\gamma_2$ \*SIGK;  $G\beta_1\gamma_2$ \* $G\alpha_{t1}$ ;  $G\beta_1\gamma_2$ \*GRK2;  $G\beta_1\gamma_1$ \*phosducin) shows that the protein interaction site residues of GP exhibit only slightly greater than average side chain positional dispersity (1.42  $\text{\AA}$  compared to 1.35  $\text{\AA}$ ), with the side chains of Trp99, Asp228, and Trp332 having the largest positive deviation from the average (each greater than 2  $\text{\AA}$ ). In particular, Arg314 and Trp332 in blade seven move more than 10  $\text{\AA}$  towards the outside of the  $G\beta_1$  torus to interact with phosducin. Atomic B factors also provide a measure of conformational flexibility. In the structure of uncomplexed  $G\beta_1\gamma_1$  the B factors for Trp99, Val100, and Met101 exceed the mean value by at least one standard deviation (Trp99 is greater than two standard deviations from the mean). In complexes with  $G\alpha_{t1}$ , GRK2, phosducin, and SIGK complexes, these binding site residues become more well-ordered with B values close to the mean and in some cases up to one standard deviation below the mean. Thus, the capacity of  $G\beta$  to recognize structurally diverse binding partners does not require a high degree of conformational flexibility for most residues in the protein interaction site of  $G\beta$ . Small structural adaptations in  $G\beta_1$  are sufficient to accommodate a range of co-evolving binding partners. Structural and mutagenic analysis demonstrates that the protein interaction site on GP can be regarded as a hot surface, co-evolved to promote tight binding with multiple protein targets. However, the mechanism by which  $G\beta\gamma$  acts as a hot surface is complex. Trp332 is the only residue which meets all four of the criteria for a hot spot, although Tyr59 and Trp99 have three of the four characteristics of hot spot residues that were tested. There are other residues in the top face of  $G\beta$  that are sensitive to mutational perturbation and are utilized in many binding partner interactions but do not exhibit the characteristics of conformational flexibility, solvent accessibility, or nonpolarity expected of hot spots. Especially notable among this group are Lys57 and Met188; both of these residues are energetically

cally significant binding determinants in G $\beta$  as shown by mutational analysis and comparison to known G $\beta\gamma$  complex structures, and yet do not meet any of the additional statistical criteria for hot spot residues.

**[0028]** Accordingly, an amino acid residue of the protein interaction site of a G $\beta$  is intended to include Lys57, Tyr59, Trp99, Val100, Met101, Leu117, Tyr145, Asp186, Met188, Asp228, Asn230, Asp246, and Trp332. By way of illustration, the location of these residues is provided in the rat G $\beta$  amino acid sequence of:

```
MGEMEQLKQE AEQLKKQIAD ARKACADITL AELVSGLEVV
GRVQMRTRRT LRGHLAKIYA MHWATDSKLL VSASQDGKLI
VWDYTTTNKV HAIPLRSSWV MTCAYAPSGN FVACGGLDNM
CSIYSLKSRE GNVKVSRELS AHTGYLSCCR FLDDNNIVTS
SGDTTCALWD IETGQQKTVF VGHTGDCMSL AVSPDYKLFI
SGACDASAKL WDVREGTCRQ TFTGHESDIN AICFFPNGEA
ICTGSDDASC RLFDLPADQE LTAYSHESII CGITSVAFSL
SGRLLFAGYD DFNCNVWDSL KCERVGVLSG HDNRVSCLGV
TADGMAVATG SWDSFLKIWN
```

(GENBANK Accession No. AAA62620; SEQ ID NO:3), wherein the protein interaction site residues are underlined.

**[0029]** Likewise, these residues are located in the same position in a human G $\beta$  having the amino acid sequence of:

```
MSELEQLRQE AEQLRNQIRD ARKACGDSTL TQITAGLDPV
GRIQMRTRRT LRGHLAKIYA MHWGTSRLL VSASQDGKLI
IWDYTTTNKV HAIPLRSSWV MTCAYAXSGN FVACGGLDNI
CSIYSLKTRE GNVRVSRELP GHTGYLSCCR FLDDNQIITS
SGDTTCALWD IETGQQTVGF AGHSGDVMSL SLAPNGRTFV
SGACDASIKL WDVRDSMCRQ TFIGHESDIN AVAFFPNGYA
FTTGSDDATC RLFDLRADQE LLMYSHDNII CGITSVAFSR
SGRLLLLAGYD DFNCNIWDAM KGDRAGVLAG HDNRVSCLGV
TDDGMAVATG SWDSFLKIWN
```

(GENBANK Accession No. AAA35922; SEQ ID NO:4), wherein the protein interaction site residues are underlined.

**[0030]** An agent which interacts with at least one of these amino acid residues of the protein interaction site of G $\beta$  can bind via various heterogeneous non-bonded interactions including, but not limited to van der Waals contacts (e.g., with methionine or leucine), polar contacts (e.g., with aspartate or asparagine), or both (e.g., with lysine, tryptophan, or tyrosine) to contribute to the energy of binding. In general, it is desirable that the agent interacts with 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12 or 13 of the amino acid residues of the protein interaction site of G $\beta$  to enhance the specificity of the agent for one or more G protein interacting proteins and therefore one or more G protein-mediated signaling pathways.

**[0031]** Determining whether the agent interacts with at least one amino acid residue of the protein interaction site of the  $\beta$  subunit can be accomplished using various in vitro or in vivo assays based on detecting protein-protein interactions between the G $\beta\gamma$  subunits and other peptides or proteins known to interact with G $\beta\gamma$  subunits (e.g., SIGK peptide, G $\alpha$  subunit, or downstream proteins). An exemplary in vitro assay has been disclosed herein. This assay consists of obtaining an isolated G $\beta\gamma$  complex; contacting the G $\beta\gamma$  complex with a test agent in the presence of a peptide that binds at least one amino acid residue of the protein interaction site of  $\beta$  subunit, (e.g., a SIGK peptide or SIGK peptide derivative of SEQ ID NO:1, SEQ ID NO:2, SEQ ID NO:5, SEQ ID NO:6, SEQ ID NO:7, SEQ ID NO:8, SEQ ID NO:9, SEQ ID NO:10, SEQ ID NO:11, SEQ ID NO:12, or SEQ ID NO:13); and detecting the ability of the agent to inhibit the binding of the peptide to the protein interaction site of the  $\beta$  subunit using, for example, an ELISA assay. Other phage displayed peptides identified in the original screen (Scott, et al. (2001) supra) could also be used.

**[0032]** Alternatively, an in vivo assay can be used to determine whether a test agent interacts with at least one amino acid residue of the protein interaction site of the  $\beta$  subunit. By way of illustration, a two-hybrid assay is contemplated where the test agent is contacted with a cell expressing G $\beta\gamma$  subunits and a peptide such as SIGK, wherein the  $\beta$  subunit is fused to, e.g., a DNA-binding domain and the SIGK peptide is fused to an activation domain. When the SIGK peptide is bound to the protein interaction site of G $\beta\gamma$ , reporter protein expression is induced. If the test agent disrupts the binding of the SIGK peptide to the protein interaction site of G $\beta\gamma$ , reporter protein expression is blocked.

**[0033]** Additional screens such as well-established computational screens or screens that detect the activity of G protein-dependent downstream proteins (e.g., PLC  $\beta$  enzymatic activity) are also contemplated for use in conjunction with the assays disclosed herein.

**[0034]** Test agents, also referred to herein as compounds, which can be screened in accordance with the methods of the present invention are generally derived from libraries of agents or compounds. Such libraries can contain either collections of pure agents or collections of agent mixtures. Examples of pure agents include, but are not limited to, proteins, polypeptides, peptides, nucleic acids, oligonucleotides, carbohydrates, lipids, synthetic or semi-synthetic chemicals, and purified natural products. Examples of agent mixtures include, but are not limited to, extracts of prokaryotic or eukaryotic cells and tissues, as well as fermentation broths and cell or tissue culture supernates. In the case of agent mixtures, the methods of this invention are not only used to identify those crude mixtures that possess the desired activity, but also provide the means to monitor purification of the active agent from the mixture for characterization and development as a therapeutic drug. In particular, the mixture so identified can be sequentially fractionated by methods commonly known to those skilled in the art which can include, but are not limited to, precipitation, centrifugation, filtration, ultrafiltration, selective digestion, extraction, chromatography, electrophoresis or complex formation. Each resulting subfraction can be assayed for the desired activity using the original assay until a pure, biologically active agent is obtained.

**[0035]** Library screening can be performed as exemplified herein or can be performed in any format that allows rapid

preparation and processing of multiple reactions. Stock solutions of the test agents as well as assay components are prepared manually and all subsequent pipetting, diluting, mixing, washing, incubating, sample readout and data collecting is done using commercially available robotic pipetting equipment, automated work stations, and analytical instruments for detecting the signal generated by the assay. Examples of such detectors include, but are not limited to, luminometers, spectrophotometers, and fluorimeters, and devices that measure the decay of radioisotopes.

**[0036]** To further evaluate the efficacy of a compound identified using a screening method of the invention, one of skill will appreciate that a model system of any particular disease or disorder involving G protein signaling can be utilized to evaluate the adsorption, distribution, metabolism and excretion of a compound as well as its potential toxicity in acute, sub-chronic and chronic studies. For example, overexpression of  $\beta\gamma$  inhibitors in NG108-15/D2 cells and rat primary hippocampal neurons has been shown to block  $\delta$ -opioid and cannabinoid receptor-induced PKA  $C\alpha$  translocation and gene expression by preventing  $\beta\gamma$  activation of adenylyl cyclase (Yao, et al. (2003) *Proc. Natl. Acad. Sci. USA* 100:14379-84). Accordingly, to analyze the efficacy of a compound of the instant invention for treating addiction, NG108-15/D2 cells and/or rat primary hippocampal neurons are contacted with said compound and the effect on PKA  $C\alpha$  translocation is determined. Compounds which block  $\delta$ -opioid and cannabinoid receptor-induced PKA  $C\alpha$  translocation will be useful in treating addiction.

**[0037]** Efficacy of compounds of the instant invention for preventing or treating heart failure can be analyzed in a genetic model of murine-dilated cardiomyopathy which involves the ablation of a muscle-restricted gene that encodes the muscle LIM protein (MLP<sup>-/-</sup>) (Arber, et al. 1997) *Cell* 88:393-403). Using this model, it has been demonstrated that a beta-adrenergic receptor kinase 1 inhibitor, BARK-ct, which binds to  $\beta\gamma$  and blocks  $\beta\gamma$ -dependent activation of beta-adrenergic receptor kinase 1 activity, can enhance cardiac contractility in vivo with or without isoproterenol (Koch, et al. (1995) *Science* 268:1350-3) and restore left ventricular size and function (Rockman, et al. (1998) *Proc. Natl. Acad. Sci.* 95:7000-7005). Similarly, compounds of the instant invention which block  $\beta\gamma$ -dependent activation of beta-adrenergic receptor kinase 1 activity will be useful in preventing or treating heart failure.

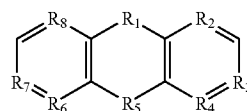
**[0038]** The effectiveness of compounds of the instant to prevent opioid tolerance can be analyzed in acute (Jiang, et al. (1995) *J. Pharmacol. Exp. Ther.* 273:680-8) and chronic (Wells, et al. (2001) *J. Pharmacol. Exp. Ther.* 297:597-605) dependence model systems, wherein mice are injected intracerebroventricularly with a compound of the instant invention and tolerance to a select opioid (e.g., morphine) is determined. Compounds which decrease the amount of opioid necessary to achieve an analgesic effect will be useful in preventing opioid tolerance.

**[0039]** PLC- $\beta$ 2 and - $\beta$ 3 and PI3K $\gamma$  have been shown to be involved in the chemoattractant-mediated signal transduction pathway. Mice deficient in PI3K $\gamma$  lack neutrophil production of PtdIns(3,4,5)P<sub>3</sub>, neutrophil migration, and production of antibodies containing the chain when immunized with T cell-independent antigen hydroxynitrophenyl-FICOLL™ (Li, et al. (2000) *Science* 287:1046-1049). Mice lacking PLC- $\beta$ 2 and - $\beta$ 3 are deficient in Ca<sup>2+</sup> release, superoxide production, and MAC-1 upregulation in neutrophils (Li, et al. (2000)

supra). Further, PLC- $\beta$ 2 deficient mice exhibit enhanced chemotaxis of different leukocyte populations and are sensitized to bacteria, viruses, and immune complexes (Jiang, et al. (1997) *Proc. Natl. Acad. Sci. USA* 94(15):7971-5). Accordingly, to analyze the efficacy of a compound of the instant invention for modulating an inflammatory response, mice can be administered said compound and the effect on neutrophil production of PtdIns(3,4,5)P<sub>3</sub>, neutrophil migration, Ca<sup>2+</sup> efflux, superoxide production, production of antibodies containing the  $\lambda$  chain when immunized with T cell-independent antigen hydroxynitrophenyl-FICOLL™ is determined. Compounds which selectively potentiate PLC- $\beta$ 2 and - $\beta$ 3 and/or block PI3K $\gamma$  activation thereby inhibiting production of PtdIns(3,4,5)P<sub>3</sub>, neutrophil migration, and production of TI-Ig $\lambda_L$ , will be useful in treating inflammatory conditions such as arthritis, allergies, Crohn's Disease and the like. Compounds which selectively block, e.g., PLC- $\beta$ 2 activation thereby facilitating neutrophil migration will be useful in facilitating immune responses to bacterial and viral infections.

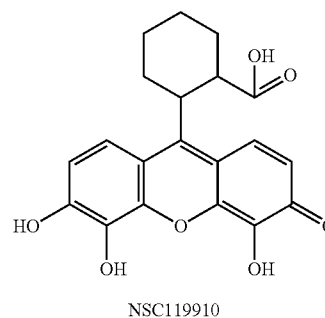
**[0040]** Using the screening method of the present invention, various compounds have now been identified which bind to the protein interaction site of a G $\beta$  subunit to interfere with or potentiate physiologically relevant protein interactions (e.g., G $\alpha$  subunit and PLC  $\beta$  interactions) thereby modulating the activity of G protein signaling pathways.

**[0041]** Accordingly, one embodiment of the present invention is a compound having a structure of Formula I:

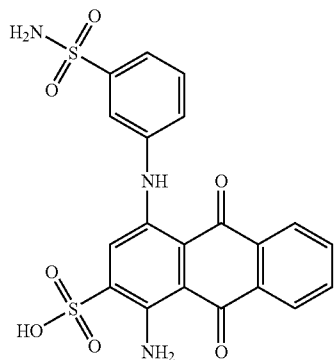


FORMULA I

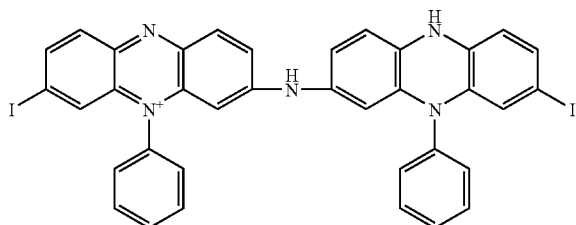
**[0042]** Exemplary compounds having the structure of Formula I which depict various substituent R groups include, but are not limited to, the following:



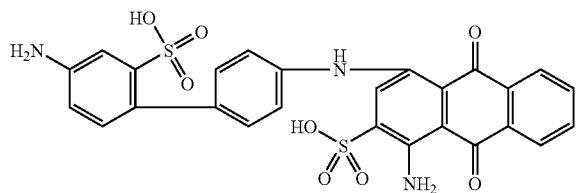
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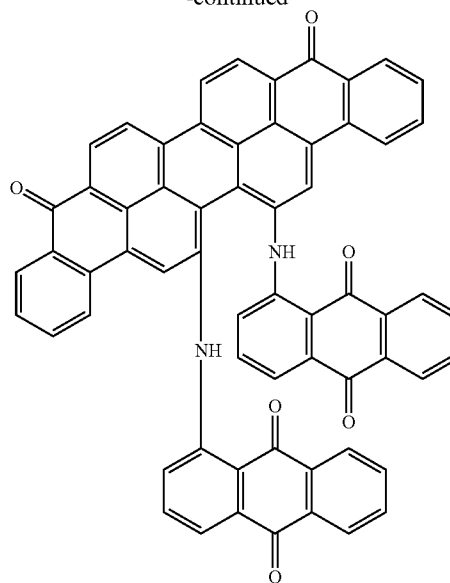


NSC402959



NSC125910

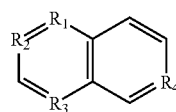
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NSC23128

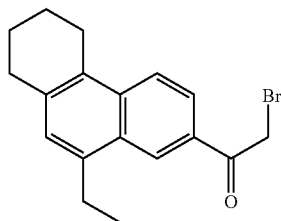
and pharmaceutically acceptable salts and complexes thereof.

[0043] Another embodiment of the present invention is a compound having a structure of Formula II:

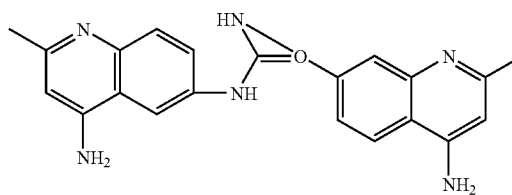


FORMULA II

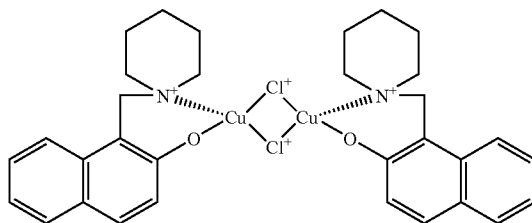
[0044] Exemplary compounds having the structure of Formula II which depict various substituent R groups include, but are not limited to, the following:



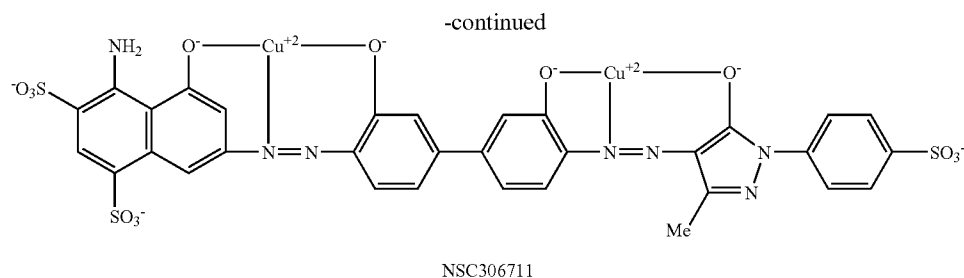
NSC30820



NSC12155

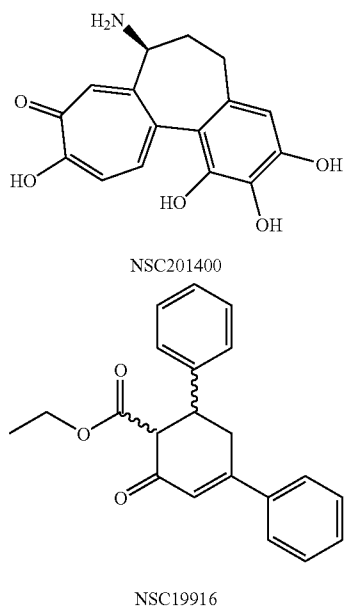


NSC109268



and pharmaceutically acceptable salts and complexes thereof.

**[0045]** Additional exemplary compounds which bind to the protein interaction site of G $\beta$  include, but are not limited to, the following:



and pharmaceutically acceptable salts and complexes thereof.

**[0046]** Exemplary compounds disclosed herein are intended to include all enantiomers, isomers or tautomers, as well as any derivatives of such compounds that retain the same biological activity as the original compound.

**[0047]** Exemplary compounds of the present invention were initially selected from a computational screen to identify ligands that bind to the novel protein interaction site of G $\beta$ . The computational screen involved using SYBYL molecular modeling software to model the protein interaction site of G $\beta$  as determined in the X-ray structure disclosed herein.

**[0048]** The computational docking screen was performed with the National Cancer Institute 1900 compound library wherein the compounds were tested for docking to the protein interaction site of G $\beta$  using FLEXX<sup>TM</sup> (Tripos, Inc., St. Louis, Mo.) for docking and CSCORE<sup>TM</sup> (Tripos, Inc.) to evaluate the energetics and fitness of the docked structure. Algorithm-dependent lists of compounds, predicted to interact with the protein interaction site of G $\beta$  and the structural model of the interaction, were generated. Selected compounds were subsequently analyzed in the phage ELISA binding assay disclosed herein to assess whether these compounds could bind to the protein interaction site of G $\beta$  and interfere with protein interactions at this surface. Compounds NSC201400 and NSC119916 had IC<sub>50</sub> values of 100 nM and 5  $\mu$ M, respectively, and the remaining compounds were found to bind in the ELISA-based assay to G $\beta$  with an affinity of at least 50  $\mu$ M and interfere with peptide interactions at the protein interaction site (FIG. 1). These compounds were further analyzed in the phage ELISA assay and found to have high affinities for the protein interaction site of G $\beta$  and interacted with similar amino acid residues as SIGK.

TABLE 2

SIGK	NSC30820	NSC12155	NSC117079	NSC23128	NSC402959	NSC109268	NSC125910	NSC119910	NSC30671
<u>Lys57</u>	<u>Lys57</u>			<u>Lys57</u>	<u>Lys57</u>		<u>Tyr59</u>	<u>Lys57</u>	<u>Lys57</u>
<u>Tyr59</u>	<u>Tyr59</u>			<u>Tyr59</u>	<u>Tyr59</u>			<u>Tyr59</u>	<u>Tyr59</u>
	Gln75			Gln75					
<u>Trp99</u>	<u>Trp99</u>			<u>Trp99</u>	<u>Trp99</u>		<u>Trp99</u>	<u>Trp99</u>	<u>Trp99</u>
<u>Val100</u>								<u>Val100</u>	
<u>Met101</u>								<u>Met101</u>	
<u>Leu117</u>					<u>Leu117</u>		<u>Leu117</u>	<u>Leu117</u>	
<u>Tyr145</u>									
<u>Asp186</u>									
<u>Met188</u>									<u>Met188</u>
						Cys204			Cys204
<u>Asp228</u>						<u>Asp228</u>			<u>Asp228</u>
<u>Asn230</u>		<u>Asn230</u>	<u>Asn230</u>			<u>Asn230</u>			

TABLE 2-continued

<u>Asp246</u>	<u>Asp246</u> <u>Thr274</u>	Arg314	<u>Asp246</u>	Thr274	Ser316	<u>Trp332</u>	Trp332	7 $\mu$ M	
<u>Trp332</u>	100 nM	13 $\mu$ M	43 $\mu$ M	16 $\mu$ M	2 $\mu$ M	13 $\mu$ M	<u>Trp332</u>	68 $\mu$ M	100 nM
IC <sub>50</sub>									

Underlined residues indicate residues important for the SIGK•G $\beta$  $\gamma$ <sub>2</sub> interaction. The last row indicates the IC<sub>50</sub> value for each compound.

**[0049]** To further illustrate the utility of these compounds, it was demonstrated that NSC119910 blocked interactions of G $\alpha$  subunit with G $\beta$  $\gamma$  subunits (FIG. 2) and inhibited the ability of G $\beta$  $\gamma$  subunits to inhibit interactions with a physiological target such as PLC  $\beta$  in vitro (FIG. 3) based on a decrease in the enzymatic activity of PLC  $\beta$ .

**[0050]** G $\beta$  $\gamma$ -regulated activities of PI3K $\gamma$  and PLC- $\beta$ 2/- $\beta$ 3 are important in chemoattractant-induced responses and inflammation. PI3K $\gamma$  is involved in the production of TI-Ig $\lambda$ <sub>L</sub> and mice deficient in PI3K $\gamma$ , lack neutrophil migration (Li, et al. (2000) *Science* 287:1046-9). The PLC pathway is involved in down-modulation of chemotaxis and in hyperinflammatory conditions (Li, et al. (2000) supra). Therefore, it was determined whether NSC119910 could inhibit the G $\beta$  $\gamma$ /PLC interaction and block PLC activation. Data from fura-2-based experiments demonstrated that the abruptly occurring increase in cytosolic Ca<sup>2+</sup> in fMLP-stimulated neutrophils, a response which is due to the release of the cation from intracellular stores (Anderson, and Mahomed (1997) *Clin. Exp. Immunol.* 110:132-138; Geiszt, et al. (1997) *J. Biol. Chem.* 272:26471-26478), was suppressed by 10  $\mu$ M NSC119910 (FIG. 4). Increases in [Ca<sup>2+</sup>] through ATP was not significantly suppressed in the presence of NSC119910 (FIG. 4), indicating that the effect of the compound on fMLP dependent Ca<sup>2+</sup> increases are specific. Further, the time taken for fluorescence to decline to half-peak values was not substantially affected (FIG. 5). The results indicate that NSC119910 inhibits PLC/G-protein interactions which lead to activation of PLC in vivo.

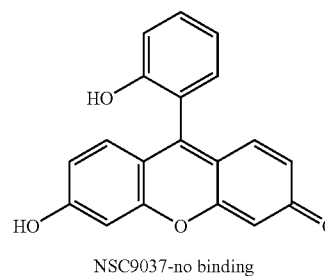
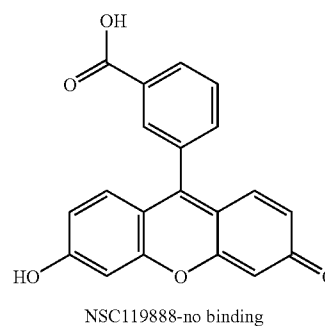
**[0051]** Opioid receptors,  $\mu$ ,  $\Delta$ , and  $\kappa$ , couple to G<sub>r</sub> and G<sub>o</sub> proteins through  $\alpha$  and  $\beta$  $\gamma$  subunits, and regulate a number of signaling pathways. In particular, the efficacy of opioid signal transduction in PLC- $\beta$ 3-deficient mice has been shown to increase, indicating that PLC suppresses opioid signaling by modification of opioid-dependent signaling components (Xie, et al. (1999) *Proc. Natl. Acad. Sci. USA* 96:10385-10390). Given that PLC- $\beta$ 3 plays a significant role as a negative regulator of opioid responses, it was determined whether NSC119910 could inhibit PLC- $\beta$ 3 activation thereby enhancing morphine-induced analgesia. Mice were intracerebroventricularly injected in accordance with standard protocols (Xu, et al. (1998) *J. Pharmacol. Exp. Therapeut.* 284:196-201) with 100 nmol of NSC119910 in combination with varying doses (0.1, 0.3, 1, and 3 nmol) of morphine. Mice were tested 20 minutes after the injection for an analgesic response in a 55° C. warm-water tail-flick test (Wells, et al. (2001) *J. Pharmacol. Exp. Therapeut.* 297:597-605). The ED<sub>50</sub> value for morphine alone was 0.74 nmol, while the ED<sub>50</sub> value for NSC119910 plus morphine was 0.065 nmol. The differences in the ED<sub>50</sub> values showed an 11-fold shift to the left in a morphine dose-response curve (Table 3), indicating that when morphine was administered with NSC119910, less morphine was required to produce a similar analgesic effect.

Accordingly, administering opioids in combination with a compound of the instant invention would allow for the use of a lower dose of opioid in patients thereby reducing the development of opioid tolerance.

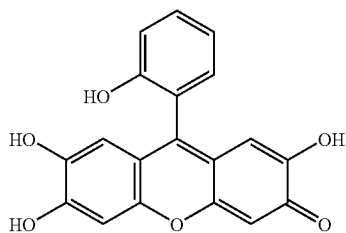
TABLE 3

Dose of Morphine, nmol	Percent Antinociception $\pm$ S.E.M.	
	Morphine Alone	Morphine plus NSC119910
10	82.4 $\pm$ 11.9	N/A
3	68.0 $\pm$ 14.1	100 $\pm$ 0.0
1	55.6 $\pm$ 8.3	79.3 $\pm$ 9.1
0.3	41.0 $\pm$ 10.2	64.4 $\pm$ 10.0
0.1	21.0 $\pm$ 11.1	55.3 $\pm$ 12.7

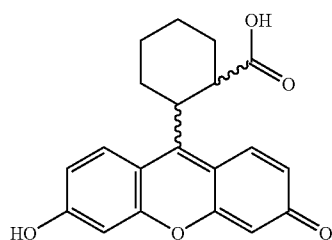
**[0052]** Having demonstrated that NSC119910 effectively modulates G-protein interactions, a series of structural analogs of NSC119910, identified using modeling software, were analyzed for binding to the protein interaction site of G $\beta$ . These analogs and their corresponding affinities for G $\beta$  were:



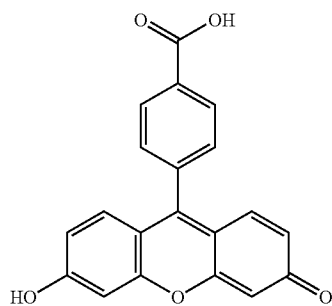
-continued



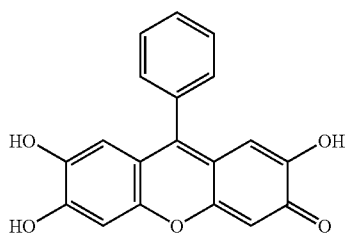
NSC158109-no binding



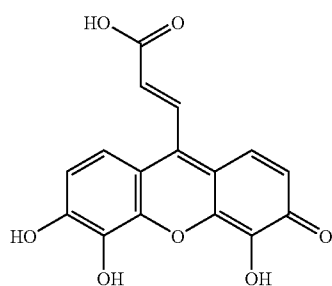
NCS119892-no binding



NSC119891-no binding

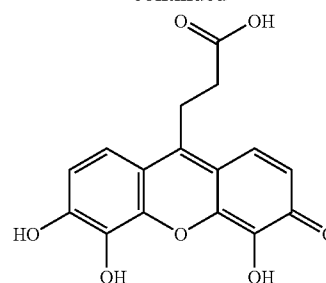


NSC2608-no binding

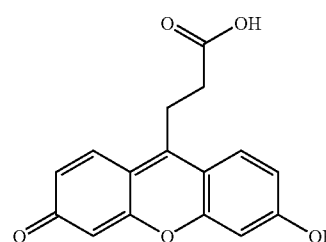


NSC119911-200 nM

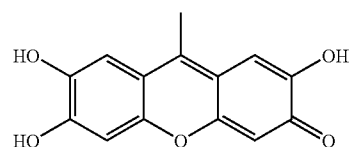
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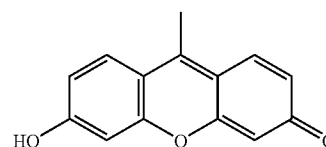
NSC119915-2.5 μM



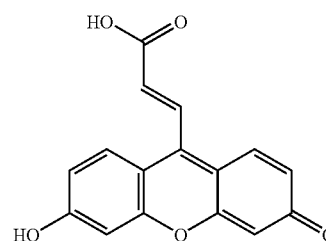
NSC158112-no binding



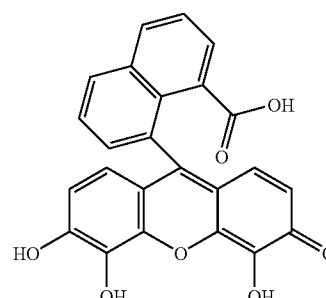
NSC5426-no binding



NSC158113-no binding

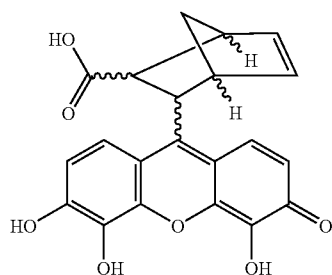


NSC119894-no binding

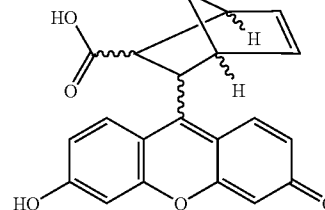


NSC119893-130 nM

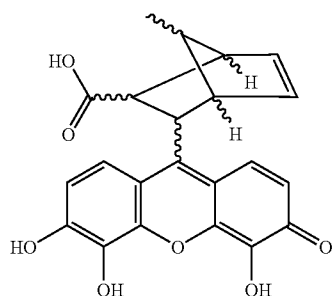
-continued

NSC119912-30  $\mu\text{M}$ 

-continued

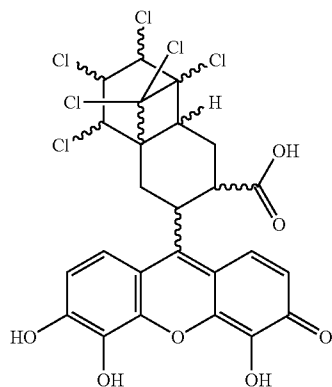
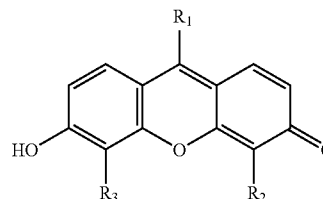
NSC122390-14  $\mu\text{M}$ 

[0053] From this analysis, a general structure for NSC119910 analogs was identified and is represented as Formula III.

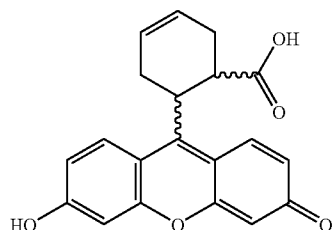


NSC119913-700 nM

FORMULA III



NSC158110-250 nM

NSC157411-7  $\mu\text{M}$ 

wherein,  $R_1$  can be a substituted or unsubstituted alkyl, substituted or unsubstituted alkenyl, substituted or unsubstituted cycloalkyl, or substituted or unsubstituted cycloalkenyl; and  $R_2$  and  $R_3$  are independently hydrogen or a hydroxyl group. In particular embodiments,  $R_2$  and  $R_3$  are both hydroxyl.

[0054] As used herein, alkyl refers to a straight or branched hydrocarbon chain consisting solely of carbon and hydrogen atoms, containing no saturation, having from one to eight carbon atoms.

[0055] Alkenyl is intended to mean an aliphatic hydrocarbon group containing at least one carbon-carbon double bond and which may be a straight or branched chain having from 2 to about 10 carbon atoms.

[0056] Cycloalkyl denotes a non-aromatic mono or multi-cyclic ring system of about 3 to 12 carbon atoms.

[0057] As used herein, the term cycloalkenyl refers to a mono or multicyclic ring system containing in the range of about 3 to 12 carbon atoms with at least one carbon-carbon double bond.

[0058] Substituents in the substituted alkyl, cycloalkyl, alkenyl or cycloalkenyl groups include, but are not limited to, hydroxy, carboxyl, halogen (e.g., fluorine, chlorine, bromine, or iodine), or substituted or unsubstituted alkyl. With the exception of NSC157411 and NSC122390, analogs of NSC119910 generally contained hydroxyl groups in the  $R_2$  and  $R_3$  positions of Formula III, which appeared to facilitate binding; and a carboxyl-substituted alkyl, cycloalkyl, alkenyl or cycloalkenyl substituent at  $R_1$  of Formula III, which appeared to modulate activity, but was not required for binding.

[0059] Accordingly, a further embodiment of the present invention is a compound having a structure of Formula III and pharmaceutically acceptable salts and complexes thereof.

[0060] The ability of NSC119910 analogs to selectively modulate activation PLC- $\beta 2$  and - $\beta 3$  was analyzed. In this

assay, PLC- $\beta$ 2 and PLC- $\beta$ 3 were purified and PLC enzymatic activity was measured in the presence or absence of purified  $\beta\gamma$  and in the presence or absence of analog. The results of this analysis indicated that NSC119911 appeared to block PLC- $\beta$ 2 activation more effectively than PLC- $\beta$ 3 activation and NSC201400 selectively potentiated PLC- $\beta$ 3 activation despite blocking peptide binding to  $\beta\gamma$  (FIG. 6). Further, while NSC119910, NSC and analog NSC119893 block  $\text{Ca}^{2+}$  mobilization, they do so without interfering with fMLP-dependent ERK activation. Likewise, NSC119911, NSC158110, and NSC201400 also do not interfere with fMLP-dependent ERK activation.

**[0061]** The compounds disclosed herein as well as those found to bind to the protein interaction site of G $\beta$  and interfere with protein interactions at this surface can be used in a method for modulating (i.e., blocking or inhibiting, or enhancing or potentiating) at least one activity of a G protein. Such a method involves contacting a G protein either in vitro or in vivo with an effective amount of an agent that interacts with at least one amino acid residue of the protein interaction site of the G protein  $\beta$  subunit so that at least one activity of the G protein is modulated. An effective amount of an agent is an amount which reduces or increases the activity of the G protein by 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% or 100%. Such activity can be monitored based on protein-protein interactions or enzymatic assays detecting activity of downstream proteins.

**[0062]** As will be appreciated by one of skill in the art, modulating one or more G protein activities can be useful in selectively analyzing G protein signaling events in model systems as well as in preventing or treating diseases and disorders involving G protein  $\beta\gamma$  subunit signaling. The selection of the compound for use in preventing or treating a particular disease or disorder will be dependent upon the particular G protein-dependent downstream protein involved in the disease or disorder. For example, a compound which interacts with Lys57, Trp99, Met101, Leu117, Asp186, Asp228, Asp246 and/or Trp332 of GP would be useful in preventing or treating adenylyl cyclase-associated diseases or disorders, whereas a compound which interacts with Lys57, Tyr59, Trp99, Met101, Leu117, Tyr146, Met188, Asp246, and/or Trp332 may be more suitable for GRK2-associated diseases or disorders. It is contemplated that this selectivity for specific downstream proteins may reduce side effects associated with antagonists which inhibit all activities associated the G protein  $\beta\gamma$  subunit signaling.

**[0063]** Prevention or treatment typically involves the steps of first identifying a patient at risk of having or having a disease or disorder involving at least one G protein  $\beta\gamma$  subunit activity (e.g., congestive heart failure, addiction, hyper- or hypo-inflammation, or opioid tolerance). Once such an individual is identified using, for example, standard clinical practices, said individual is administered a pharmaceutical composition containing an effective of a selective compound disclosed herein or identified in the screening methods of the invention. In most cases this will be a human being, but treatment of agricultural animals, e.g., livestock and poultry, and companion animals, e.g., dogs, cats and horses, is expressly covered herein. The selection of the dosage or effective amount of a compound is that which has the desired outcome of reducing or reversing at least one sign or symptom of a disease or disorder involving G protein  $\beta\gamma$  subunit signaling in a patient. For example, some of the general signs or symptoms associated with congestive heart failure include increased heart rate, increased respiratory rate, breathing faster and deeper than normal, breathlessness, irritability, restlessness, an unexplained fussiness, swelling, puffiness,

edema, sudden weight gain or poor weight gain, decrease in appetite, diaphoresis, cough, congestion or wheezing, a decrease in activity level, fatigue, listlessness, decrease in urine output, or pale, mottled or grayish appearance in skin color. General signs or symptoms associated with addiction include, but are not limited to, changes in attitude, appearance, and relationships with others, whether at home, school or work and other behavioral changes.

**[0064]** When preventing or treating an inflammatory condition, the selective modulation of either the PLC pathway or PI3K $\gamma$  will be useful in treating different inflammatory conditions. For example, to reduce neutrophil migration into sites of inflammation (e.g., in arthritis) it is desirable to administer a compound which selectively inhibits the activation of PI3K $\gamma$  thereby reducing the injury to tissues that contribute to the pathophysiology of the inflammatory diseases. Conversely, to facilitate an inflammatory response, e.g., to enhance immune responses to bacterial or viral infection, it is desirable to administer a compound which selectively inhibits the activation of the PLC pathway.

**[0065]** Pharmaceutical compositions can be in the form of pharmaceutically acceptable salts and complexes and can be provided in a pharmaceutically acceptable carrier and at an appropriate dose. Such pharmaceutical compositions can be prepared by methods and contain carriers which are well known in the art. A generally recognized compendium of such methods and ingredients is Remington: The Science and Practice of Pharmacy, Alfonso R. Gennaro, Editor, 20th ed. Lippincott Williams & Wilkins: Philadelphia, Pa., 2000. A pharmaceutically-acceptable carrier, composition or vehicle, such as a liquid or solid filler, diluent, excipient, or solvent encapsulating material, is involved in carrying or transporting the subject compound from one organ, or portion of the body, to another organ, or portion of the body. Each carrier must be acceptable in the sense of being compatible with the other ingredients of the formulation and not injurious to the patient.

**[0066]** Examples of materials which can serve as pharmaceutically acceptable carriers include sugars, such as lactose, glucose and sucrose; starches, such as corn starch and potato starch; cellulose, and its derivatives, such as sodium carboxymethyl cellulose, ethyl cellulose and cellulose acetate; powdered tragacanth; malt; gelatin; talc; excipients, such as cocoa butter and suppository waxes; oils, such as peanut oil, cottonseed oil, safflower oil, sesame oil, olive oil, corn oil and soybean oil; glycols, such as propylene glycol; polyols, such as glycerin, sorbitol, mannitol and polyethylene glycol; esters, such as ethyl oleate and ethyl laurate; agar; buffering agents, such as magnesium hydroxide and aluminum hydroxide; alginic acid; pyrogen-free water; isotonic saline; Ringer's solution; ethyl alcohol; pH buffered solutions; polyesters, polycarbonates and/or polyanhydrides; and other non-toxic compatible substances employed in pharmaceutical formulations. Wetting agents, emulsifiers and lubricants, such as sodium lauryl sulfate and magnesium stearate, as well as coloring agents, release agents, coating agents, sweetening, flavoring and perfuming agents, preservatives and antioxidants can also be present in the compositions.

**[0067]** The compositions of the present invention can be administered parenterally (for example, by intravenous, intraperitoneal, subcutaneous or intramuscular injection), topically (including buccal and sublingual), orally, intranasally, intravaginally, or rectally according to standard medical practices.

**[0068]** The selected dosage level will depend upon a variety of factors including the activity of the particular compound of the present invention employed, the route of administration, the time of administration, the rate of excretion or metabolism

of the particular compound being employed, the duration of the treatment, other drugs, compounds and/or materials used in combination with the particular compound employed, the age, sex, weight, condition, general health and prior medical history of the patient being treated, and like factors well known in the medical arts.

**[0069]** A physician or veterinarian having ordinary skill in the art can readily determine and prescribe the effective amount of the pharmaceutical composition required. For example, the physician or veterinarian could start doses of a compound at levels lower than that required in order to achieve the desired therapeutic effect and gradually increase the dosage until the desired effect is achieved. This is considered to be within the skill of the artisan and one can review the existing literature on a specific compound or similar compounds to determine optimal dosing.

**[0070]** As will be understood by those of skill in the art upon reading this disclosure, additional compounds to those exemplified herein can be identified routinely in accordance with the screening methods taught herein. Additional compounds for screening can be selected randomly by one skilled in the art, based upon computational prediction, and/or based upon their containing a structure of Formula I, II or III or a structure similar to that of the exemplary compounds disclosed herein.

**[0071]** The invention is described in greater detail by the following non-limiting examples.

#### EXAMPLE 1

##### Materials

**[0072]** Peptides were purchased from Alpha Diagnostic International (San Antonio, Tex.) or SIGMA®-Genosys (St. Louis, Mo.), HPLC purified to greater than 90% and masses confirmed by mass spectroscopy. Ni-NTA agarose was from QIAGEN® (Valencia, Calif.). Streptavidin-coated poly-styrene beads were from Spherotec (Libertyville, Ill.). HRP-conjugated anti-M13 antibody was from Amersham Biosciences (Piscataway, N.J.). HRP-conjugated Neutravidin was from Pierce (Rockford, Ill.). All molecular biology reagents were from INVITROGEN™ (Carlsbad, Calif.) unless otherwise indicated.

#### EXAMPLE 2

##### Expression and Purification of Gβ<sub>1</sub>γ<sub>2</sub> and SIGK Peptide

**[0073]** Baculoviruses harboring cDNA for wild-type bovine Gβ<sub>1</sub> and N-terminally (His)<sub>6</sub>-tagged bovine Gγ<sub>2</sub> were used to produce proteins of the same. High 5 cells (INVITROGEN™, Carlsbad, Calif.; 2×10<sup>6</sup> cells/mL) were infected with high titer Gβ<sub>1</sub> and Gγ<sub>2</sub> baculoviruses. Gβ<sub>1</sub>γ<sub>2</sub> was purified according to standard methods (Kozasa and Gilman (1995) *J. Biol. Chem.* 270:1734-41), with modifications. All steps were carried out at 4° C. Cells were harvested 60 hours post-infection by centrifugation at 2600 g, then resuspended in 50 mL of lysis buffer (20 mM HEPES, pH 8, 150 mM NaCl, 5 mM β-ME, 1 mM EDTA, 1 mL SIGMA® protease inhibitor cocktail P-2714) per liter of cell culture. Cells were lysed by sonication and centrifuged at 2600 g to pellet the membranes. Resuspension and homogenization of membranes was accomplished by douncing in 100 mL lysis buffer. The membranes were solubilized by adding 1% Lubrol (Cl<sub>2</sub>E10, SIGMA®, St. Louis, Mo.) with stirring and the resultant solution clarified by ultracentrifugation at 125,000 g. The supernatant was loaded onto Ni-NTA agarose (QIAGEN®, Valencia, Calif.) equilibrated with lysis buffer+1% Lubrol.

The column was washed and the Lubrol exchanged for sodium cholate using buffers Ni-A (20 mM HEPES, pH 8, 0.4 M NaCl, 5 mM β-ME, 0.5% Lubrol, 0.15% cholate) and Ni-B (20 mM HEPES pH 8, 0.1 M NaCl, 5 mM β-ME, 0.25% Lubrol, 0.3% cholate). Gβ<sub>1</sub>γ<sub>2</sub> eluted in Ni-C (20 mM HEPES pH 8, 0.01 M NaCl, 5 mM β-ME, 1% cholate, 200 mM imidazole). The eluate was loaded onto a HITRAP™ Q (Amersham Biosciences, Piscataway, N.J.) column pre-equilibrated with QA (20 mM HEPES, pH 8, 5 mM β-ME, 0.7% CHAPS, 1 mM EDTA). Gβ<sub>1</sub>γ<sub>2</sub> eluted in a gradient using QB (QA+1.0 M NaCl). Fractions containing Gβ<sub>1</sub>γ<sub>2</sub> were analyzed by SDS-PAGE and pooled. Gel filtration was performed using a tandem SEPHADEX® 75:SEPHADEX® 200 column (Amersham Biosciences, Piscataway, N.J.) equilibrated with buffer GF+CHAPS (20 mM HEPES, pH 8, 150 mM NaCl, 10 mM β-ME, 1 mM EDTA, 0.7% CHAPS). The purified yield was typically 1 mg Gβ<sub>1</sub>γ<sub>2</sub> per liter of cell culture.

**[0074]** SIGK peptide (Ser-Ile-Gly-Lys-Ala-Phe-Lys-Ile-Leu-Gly-Tyr-Pro-Asp-Tyr-Asp; SEQ ID NO:2) was synthesized using well-established methods. No modifications were made to the peptide termini; purification was by reverse phase-HPLC chromatography on a VYDAC® C4 semi-preparative column.

#### EXAMPLE 3

##### Crystallography

**[0075]** SIGK peptide was added to Gβ<sub>1</sub>γ<sub>2</sub> in 1.5 molar excess, and the Gβ<sub>1</sub>γ<sub>2</sub>•SIGK complex was used at 7 mg/mL for crystallization. Crystals were grown by vapor diffusion using equal volumes (2 μL) of protein and reservoir solution (15-17% PEG 4000, 100 mM HEPES, pH 7.5, 0.01-0.05 M Na-Acetate, 10% glycerol) at 20° C. Crystals attained dimensions of 150 μm×50 μm×20 μm within one week. Crystals were cryoprotected in 15% glycerol and frozen in liquid nitrogen.

**[0076]** Native crystals of Gβ<sub>1</sub>γ<sub>2</sub>•SIGK were screened at Advanced Light Source (ALS) beamlines 8.2.1 and 8.2.2 (Berkeley, Calif.) and at the Advanced Photon Source (APS) beamline BM-19 (Chicago, Ill.). A dataset from ALS 8.2.2 was used to determine the structure. Over 100 crystals were screened; diffraction limits varied from 7 Å to the 2.7 Å dataset used for structure determination. Diffraction data were indexed, integrated, and scaled using the software package HKL2000 (Otwinowski and Minor (1997) In: *Methods in Enzymology*, Vol. 276:307-326) (Table 4). The space-group of the crystals was P2<sub>1</sub>2<sub>1</sub>2<sub>1</sub>.

TABLE 4

Data Collection	
Space Group Unit Cell	P2 <sub>1</sub> 2 <sub>1</sub> 2 <sub>1</sub>
a (Å)	45.468
b	74.669
c	108.023
α (°)	90
β	90
γ	90
D <sub>min</sub> (Å)	2.7
Unique Reflections	9729
Redundancy <sup>1</sup>	3.5 (1.8)
Completeness (%) <sup>1</sup>	90.1 (56.2)
<I/σ> <sup>1</sup>	13.5 (1.6)

TABLE 4-continued

Rsym <sup>1,2</sup>	8.7 (41.4)
Mosaicity (°)	2.3
Wilson B-factor (Å)	61.8
<u>Refinement</u>	
Resolution (Å)	45.4-2.7
Number of atoms <sup>3</sup>	
Protein	
Water	
R <sub>work</sub> (%) <sup>4</sup>	
R <sub>free</sub> (%) <sup>5</sup>	
<u>R.m.s Deviations</u>	
Bond lengths (Å)	0.006
Bond Angles (°)	1.3
<u>R.m.s. B factors (Å<sup>2</sup>)</u>	
Bonded main chain	1.29
Bonded side chain	18.1
Average B-factor (Å) <sup>6</sup>	46.3

The final model contains residues 2-340 of Gβ<sub>1</sub> (of 340), 7-52 of Gγ<sub>2</sub> (of 68), 1-13 of SIGK (of 15), and 37 water molecules.

<sup>1</sup>Numbers in parentheses correspond to the highest resolution shell, 2.8-2.7 Å.

<sup>2</sup> $R_{sym} = \sum_h \sum_i |I_i(h) - \langle I(h) \rangle| / \sum_h \sum_i I_i(h)$ , where  $I_i(h)$  and  $\langle I(h) \rangle$  are the  $i^{th}$  and mean measurement of the intensity of reflection  $h$ , respectively.

<sup>3</sup>The final model contains residues 2-340 of Gβ<sub>1</sub> (of 340), 7-52 of Gγ<sub>2</sub> (of 68), and 1-13 of SIGK (of 15).

<sup>4</sup> $R_{work} = \sum_h ||F_o(h)| - |F_c(h)|| / \sum_h |F_o(h)|$ , where  $F_o(h)$  and  $F_c(h)$  are the observed and calculated structure factors, respectively. An  $1/\sigma$  cutoff was not used in the final calculations of R-factors.

<sup>5</sup>R<sub>free</sub> is the R-factor obtained for a test set of reflections consisting of a randomly selected 8% of the data.

<sup>6</sup>B-factors at the N-termini, including Gβ<sub>1</sub> residues 2-41 and Gγ<sub>2</sub> residues 7-13, are greater than 80 Å<sup>2</sup>.

**[0077]** The structure of the Gβ<sub>1</sub>γ<sub>2</sub>•SIGK complex was solved by the molecular replacement method using the program PHASER (Storoni, et al. (2004) *Acta Crystallogr. D Biol. Crystallogr.* 60:432-8; Read (2001) *Acta Crystallogr. D Biol. Crystallogr.* 57:1373-82). The coordinates of Gβ<sub>1</sub>γ<sub>2</sub> in the Gβ<sub>1</sub>γ<sub>2</sub>•GRK2 complex (10 MW, 100% sequence identity) were used as the search model. After rigid body refinement using the maximum likelihood minimization target in CNS version 1.1 (Adams, et al. (1997) *Proc. Natl. Acad. Sci. USA* 94:5018-23; Brunger, et al. (1998) *Acta Crystallographica Section D* 54:905-921), the model was further refined by using a combination of simulated annealing, Powell minimization, and B factor refinement. The sigma A-weighted 2Fo-Fc electron density map computed with refined phases revealed clear main chain density for ten residues of the SIGK peptide along with identifiable side chain density for several SIGK residues. Subsequent model building was performed in O (Jones, et al. (1991) *Acta Crystallographica Section A* 47:110-119) followed by simulated annealing, energy minimization, and B factor refinement using CNS. PROCHECK (Laskowski, et al. (1993) *J. Appl. Crystallography* 26:283-291) analysis indicates that all residues exhibit main chain conformations in most favored or additional allowed regions of  $\phi$ ,  $\psi$  space (Table 4). Calculations of surface accessibility, Gβ<sub>1</sub>γ<sub>2</sub>•SIGK contacts and RMSD between structures were carried out using programs in the CNS suite.

#### EXAMPLE 4

##### Construction and Partial Purification of Biotinylated Gβ<sub>1</sub>γ<sub>2</sub> (b-βγ) and b-βγ Mutants

**[0078]** Wild-type Gβ<sub>1</sub> and Gβ<sub>1</sub> mutants were made in the baculovirus vector PDW464 which encodes a biotinylation

site at a lysine upstream of the amino terminus of Gβ<sub>1</sub> (Goubaeva, et al. (2003) supra). Mutants were generated by overlap extension PCR using standard protocols. The wild-type and mutant Gβ<sub>1</sub> constructs consisted of a 20 amino acid biotin acceptor peptide (BAP) sequence fused in-frame with the amino-terminus of rat Gβ<sub>1</sub> subunit. When coexpressed with biotin holoenzyme synthetase (BirA) in Sf9 cells, the Gβ<sub>1</sub> subunit becomes covalently biotinylated in vivo at the specific lysine acceptor residue in the BAP. Using this approach, 1-2 mg protein of purified protein can be obtained per liter of Sf9 insect cells. As 45 ng of protein is used in the phage ELISA assay, a single purification is sufficient for 10,000 to 30,000 binding assays.

**[0079]** Baculoviruses were generated via the BAC-TO-BAC® system following the manufacturer's instructions (GIBCO/BRL, Gaithersburg, Md.). Sf9 cells (200 mL) were triply infected with 0.5 mL baculovirus encoding (H is)<sub>6</sub>-Gα<sub>i1</sub>, 4 mL of Gγ<sub>2</sub> virus, and 4 mL of either wild-type or mutated Gβ<sub>1</sub> virus. Gβ<sub>1</sub>γ<sub>2</sub> dimers were purified 60 hours post-infection using a well-established method with modifications as indicated (Kozasa and Gilman (1995) supra). Cell pellets were lysed in 4 mL lysis buffer (50 mM HEPES, pH 8.0, 3 mM MgCl<sub>2</sub>, 10 mM β-mercaptoethanol, 1 mM EDTA, 100 mM NaCl, 10 μM GDP, and protease inhibitors) by four freeze-thaw cycles in liquid nitrogen. Membranes were solubilized using 1% sodium cholate, clarified by ultracentrifugation at 100,000 g for 20 minutes, diluted into buffer containing 0.5% lubrol, and mixed with Ni-NTA resin. After washing thoroughly, Gβ<sub>1</sub>γ<sub>2</sub> subunits were eluted from bound Gα<sub>i1</sub> by mixing beads with buffer containing 50 mM MgCl<sub>2</sub>, 10 mM NaF, 10 μM AlCl<sub>3</sub>, 1% cholate, and 5 mM imidazole at room temperature for one hour. The concentrations of b-βγ and b-βγ mutants were analyzed by comparative immunoblotting and chemiluminescence. Proteins were separated by SDS-PAGE, transferred to nitrocellulose, and probed with HRP-neutravidin (Pierce, Rockford, Ill.). The chemiluminescent signal was measured using an EPI-CHEM II™ darkroom system (UVP Bioimaging Systems, Upland, Calif.). Concentrations of eluted b-βγ dimers were determined by comparing to a standard curve of fully purified 100% biotinylated Gβ<sub>1</sub>γ<sub>2</sub> from at least two separate gels.

#### EXAMPLE 5

##### b-βγ Binding Assay

**[0080]** Phage ELISA assays used to assess peptide binding to wild-type and mutant b-βγ were performed according to standard methods (Smrcka and Scott (2002) *Methods Enzymol.* 344:557-76). Briefly, 1 μg streptavidin was immobilized in the well of a 96-six well plate overnight at 4° C. The wells were blocked with 100 μL of 2% bovine serum albumin (BSA) in Tris-buffered saline (TBS) for 1 hour at 4° C. followed by three washes of 1×TBS/0.5% TWEEN®. Forty μL of 25 nM bGβ<sub>1</sub>γ<sub>2</sub> in TBS/0.5% TWEEN® was added to each well and incubated at 4° C. for 1.5 hour. The wells were washed, followed by the addition of 1×10<sup>6</sup> to 1×10<sup>10</sup> phage particles and incubated at 4° C. for 3 hours. The wells were then washed six times with TBS/0.5% TWEEN® followed by addition of 40 μL of 1:5000 dilution of anti-M13 antibody (Pharmacia, Uppsala, Sweden) and incubated at room temperature for 1 hour. The wells were washed, followed by the addition of 40 μL of (2,2'-Azino-bis(3-ethylbenzthiazoline)-

6-sulfonic acid (ABTS) and the calorimetric reaction was monitored at 405 nm. Non-specific binding was subtracted for each reading.

**[0081]** Signals obtained with partially purified b- $\beta\gamma$  subunits were similar to signals obtained from fully purified b- $\beta\gamma$  subunits. Blocking of  $G\alpha_i \cdot G\beta_1\gamma_2$  binding was assessed by simultaneously adding 200 pM FITC- $G\alpha_i$  with or without SIGK to 50 pM immobilized b- $\beta\gamma$  and measuring the amount of FITC- $G\alpha_i$  bound to the beads by flow cytometry according to standard methods (Ghosh, et al. (2003) supra; Sarvazyan, et al. (1998) *J. Biol. Chem.* 273:7934-40).

#### EXAMPLE 6

##### Architecture of the $G\beta_1\gamma_2 \cdot \text{SIGK}$ Complex

**[0082]** Unless indicated otherwise, amino acid residues having the prefix “s” are indicative of SIGK residues.

**[0083]**  $G\beta_1$  is a  $\beta$ -propeller composed of seven four-stranded  $\beta$ -sheets (“blades”) and an N-terminal extended helix that interacts extensively with  $G\gamma_2$ . Each sheet is composed of WD-40 repeats connected by loops of variable length. Residues 2-340 of  $G\beta_1$  are included in the model. B factors throughout the core of  $G\beta_1$  are less than 40  $\text{\AA}^2$ . Residues with B factors  $>60 \text{\AA}^2$  are found in three loop regions: Lys127-Ser136 in blade two, Arg214-Met217 in blade four, and Ser265-Ile269 in the loop connecting blades six and seven.  $G\gamma_2$  forms a helix with a kink made by residues Asn24-Lys29 and a coil region beginning at residue His44. The average B factor within the  $G\gamma_2$  molecule is 44  $\text{\AA}^2$ . No electron density was observed for the N-terminal seven residues and the C-terminal sixteen residues of  $G\gamma_2$  or the prenyl lipid modification at the C-terminus of  $G\gamma_2$ .

**[0084]** SIGK forms an  $\alpha$ -helical structure broken by a glycine at position 10. The C-terminal three residues form an extended structure that stretches away from the  $G\beta_1$  molecule and is supported by crystal contacts between sPro12 and sAsp13 with Thr47 and Lys337 from a symmetry-related  $G\beta_1$  molecule. The B factors for the N-(sSer1, sIle2) and C-terminal (sGly10-sAsp13) residues of SIGK are greater than 50  $\text{\AA}^2$ ; those for all other residues are between 30-50  $\text{\AA}^2$ . The electron density for the main chain atoms in residues 1-13 is well-defined; three of the SIGK side chains that do not contact  $G\beta_1$  (sIle2, sLys7, and sAsp13) are disordered. The peptide binds across the “top” face of  $G\beta_1$  and is buried 970  $\text{\AA}^2$  total solvent-accessible surface area. The peptide makes no contact with the  $G\gamma_2$  subunit, which is bound to the “bottom” surface of the  $G\beta_1$  torus.

**[0085]** The SIGK contact surface on  $G\beta_1$  was separated into two regions: an acidic region on  $G\beta_1$  that interacts with the N-terminus of the peptide, and a largely nonpolar region that interacts with the C-terminus of the peptide. In total, thirteen  $G\beta_1$  residues directly contact SIGK, contributed by six of the seven blades of the  $\beta$ -propeller (Table 5).

TABLE 5

	G $\beta_1$ -Interacting Residues		SIGK-Interacting Residues		Distance ( $\text{\AA}$ )	Type of Interaction
Lys57	Ce	Leu9	O		3.35	Nonpolar
	Ce	Gly10	C $\alpha$		3.99	Nonpolar
Tyr59	OH	Leu9	O		2.66	Polar
	Ce	Ile8	O		3.87	Nonpolar
Trp99	Ne1	Tyr11	OH		2.81	Polar
	C $\delta$ 1	Leu9	C $\delta$ 2		3.59	Nonpolar

TABLE 5-continued

	G $\beta_1$ -Interacting Residues		SIGK-Interacting Residues		Distance ( $\text{\AA}$ )	Type of Interaction
Val100	O		Leu9	C $\delta$ 2	3.75	Nonpolar
Met101	Ce		Ile8	C $\gamma$ 2	3.46	Nonpolar
	Ce		Ala5	O	3.52	Nonpolar
Leu117	Ce		Leu9	C $\delta$ 2	3.54	Nonpolar
	C $\delta$ 1		Ile2	C $\gamma$ 2	3.46	Nonpolar
	C $\delta$ 2		Ala5	C $\beta$	3.68	Nonpolar
Tyr145	C $\delta$ 2		Leu9	C $\delta$ 1	3.80	Nonpolar
	Ce2		Ser1	O	3.19	Nonpolar
	OH		Lys4	C $\gamma$	3.45	Nonpolar
Asp186	C $\delta$ 2		Ala5	C $\beta$	3.81	Nonpolar
	O $\delta$ 2		Ser1	O	3.03	Polar
Met188	Ce		Ile8	C $\delta$ 1	3.31	Nonpolar
	Ce		Lys4	Ce	3.48	Nonpolar
Asp228	C $\delta$ 2		Lys4	N $\zeta$	3.23	Polar
Asn230	N $\delta$ 2		Lys4	N $\zeta$	2.82	Polar
Asp246	O $\delta$ 2		Lys4	N $\zeta$	3.05	Polar
Trp332	C $\zeta$ 2		Ile8	O	3.12	Nonpolar
	CH2		Gly10	C $\alpha$	3.57	Nonpolar

**[0086]** The N-terminal binding surface is centered on an electrostatic interaction in which sLys4 projects into a negatively charged binding pocket on  $G\beta_1\gamma_2$  where it forms hydrogen-bonded or charge interactions with Asp228, Asn230, and Asp246. A hydrogen bond between the carbonyl oxygen of Asp228 and the main chain nitrogen of Asp246 stabilizes the three acidic residues on  $G\beta_1$ . Met188 participates in van der Waals interactions with the alkyl chain of sLys4, and Asp186 forms a polar contact with the carbonyl oxygen of sSer1 and also makes a hydrogen bond to the amide of Cys204. Additionally, Tyr145 forms van der Waals interactions with the main chain oxygen of sSer1, the sLys4 side chain, and the C $\beta$  atom of sAla5, and forms a hydrogen bond with the nearby amide of Gly162. The side chain of Leu117 is within van der Waals contact distances of the side chains of sIle2 and sAla5. Together, these nine  $G\beta_1$  residues form a surface that tethers SIGK to  $G\beta_1$  using charged and nonpolar interactions.

**[0087]** Mutational analysis of SIRK and SIGK peptides can now be interpreted in the context of the SIGK $\cdot G\beta_1\gamma_2$  structure (Scott, et al. (2001) supra; Goubaeva, et al. (2003) supra). Wild-type SIRK peptide inhibits the activation of PLC  $\beta$ 2 by  $G\beta_1\gamma_2$  with an  $IC_{50}$  of 5  $\mu\text{M}$ . Substitution of sLys4 with alanine in the SIRK peptide lowers the  $IC_{50}$  of the peptide 12-fold, and mutation of sAla5 to glycine lowers the  $IC_{50}$  by 13-fold. Mutation of sIle2 to alanine reduces  $IC_{50}$  of the peptide by 4-fold, and mutation of sSer1 to alanine has no effect on  $IC_{50}$  (Scott, et al. (2001) supra). The SIGK $\cdot G\beta_1\gamma_2$  structure indicates that the main chain of sSer1 and the side chains of sIle2, sLys4, and sAla5 contact multiple residues on GP, thereby explaining this mutational data.

**[0088]** To measure the contribution of the  $G\beta_1$  residues observed at the  $G\beta_1\gamma_2 \cdot \text{SIGK}$  interface to the binding energy for the complex, two approaches were utilized. First, an ELISA assay was used to measure binding of immobilized  $G\beta_1\gamma_2$  subunits to phage displaying the SIGK sequence (Table 6). The ELISA binding data were then correlated with  $IC_{50}$  values for SIGK as a competitor of  $G\beta_1\gamma_2$  association with  $G\alpha_{i1}$  (Table 7). Both assays were then carried out with  $G\beta_1\gamma_2$  heterodimers containing mutations in the  $G\beta_1$  subunit. In the N-terminal binding surface, mutation of  $G\beta_1$  Asn230 to alanine decreased the affinity of  $G\beta_1\gamma_2$  for peptide 10-fold (Table 6). Single mutation of  $G\beta_1$  residues Asp186, Met188, Tyr145, and Leu117 to alanine also resulted in  $G\beta_1\gamma_2$  dimers

with drastically decreased affinity for SIGK (Table 6). G $\beta_1$  mutants in which either Asp228 or Asp246 were substituted with alanine did not dimerize with G $\gamma_2$  and therefore were not analyzed. However, a mutant in which Asp228 was substituted with serine caused only a slight loss in binding affinity for SIGK peptide (Table 6). Thus, many of the G $\beta_1$  residues that create the N-terminal SIGK binding interface contribute strongly to the energy of binding.

TABLE 6

G $\beta_1\gamma_2$ Mutation	% of Wild-Type Signal (mean $\pm$ SD)
Lys57Ala	18.6 $\pm$ 4.6
Tyr59Ala	24.7 $\pm$ 15.2
His62Ala	111.2 $\pm$ 11.3
Trp99Ala	66.0 $\pm$ 7.7
Met101Ala	32.2 $\pm$ 15.5
Leu117Ala	2.1 $\pm$ 2.4
Tyr145Ala	0.8 $\pm$ 0.9
Asp186Ala	13.0 $\pm$ 13.1
Met188Ala	2.5 $\pm$ 3.7
Asn230Ala	22.4 $\pm$ 4.2
Asp246Ser	66.5 $\pm$ 7.5
Phe292Ala	109.1 $\pm$ 21.4
His311Ala	94.3 $\pm$ 18.9
Arg314Ala	50.2 $\pm$ 5.0
Trp332Ala	7.1 $\pm$ 3.7

Amino acids that contact the SIGK peptide were individually mutated to alanine (or serine for Asp246) and binding to peptide was assayed using a phage ELISA. Immobilized b- $\beta$ 1 was incubated with phage displaying SIGK peptide. Phage binding was detected using an  $\alpha$ -phage antibody; the raw data was absorbance at 405 nm. Data shown are the mean  $\pm$  SD of triplicate determinations from three independent experiments.

TABLE 7

Log [SIGK] M	% Maximal Fc Binding ( $\pm$ SD)			
	Wild-Type	Met188Ala	Trp332Ala	Arg314Ala
-7	100.0 $\pm$ 0.0	100.0 $\pm$ 0.0	100.0 $\pm$ 0.0	100.0 $\pm$ 0.0
-5.7	55.0 $\pm$ 10.8	101.3 $\pm$ 7.6	72.7 $\pm$ 2.3	65.3 $\pm$ 5.8
-5	45.7 $\pm$ 16.3	80.7 $\pm$ 7.6	57.3 $\pm$ 7.2	47.0 $\pm$ 11.1
-4.7	17.3 $\pm$ 3.8	72.7 $\pm$ 11.2	33.0 $\pm$ 3.5	30.7 $\pm$ 4.2
-4.4	13.3 $\pm$ 1.5	40.0 $\pm$ 7.1	24.7 $\pm$ 3.5	21.0 $\pm$ 0.0
-4.1	5.8 $\pm$ 4.8	33.0 $\pm$ 7.2	16.7 $\pm$ 1.2	13.0 $\pm$ 3.0

SIGK competition for FITC-G $\alpha_1\beta_1\gamma_2$  interactions with representative G $\beta_1$  subunit mutants. SIGK and FITC- $\alpha_1$  were simultaneously added to streptavidin beads coated with wild-type or mutant b- $\beta$ 1 protein and the amount of FITC- $\alpha_1$  bound to the beads was assayed by flow cytometry. Data are shown as the mean of triplicate determinants  $\pm$  standard deviation of a representative experiment.

The experiment was repeated two (Met188A) or three (wild-type, Arg314A, Trp332A) times with similar results. Comparison of the two assays over a selection of mutants that spanned the range of SIGK binding affinities indicates that a 50% loss of binding translates into a five-fold increase in IC<sub>50</sub>, a 75% loss of binding corresponds to a 10-fold increase, a 90% loss is a 20-fold shift and a 98% loss is a 50-fold shift. The IC<sub>50</sub> values are as follows: wild-type = 0.47  $\mu$ M, Arg314A = 1.5  $\mu$ M, Trp332A = 9  $\mu$ M, and Met188A = 22  $\mu$ M.

**[0089]** The second area of binding involves most of the C-terminal residues of SIGK (sAla5-sGly11), which pack against a largely hydrophobic pocket on G $\beta_1$ . This pocket extends 11 Å from Trp332 on blade seven to Met188 in blade two. Eight G $\beta_1$  residues are in direct contact with the C-terminal surface of SIGK, and two more G $\beta_1$  residues support the residues directly involved in the SIGK interaction. Met188, which interacts with sLys4 in the N-terminal interface, is also within contact distance of the side chain of sLeu8.

SIGK residues sAla5, sLeu8 and sLeu9 are complimented by van der Waals interactions with Leu117, Met101, Trp99, Tyr59 and the alkyl chain of Lys57. The main chain oxygen of Val100 interacts with the side chain of sLeu9. The indole imine of Trp99 forms a hydrogen bond with the hydroxyl group of sTyr11 and the side chain of Trp332 makes contact with the main chain oxygen of sIle8 and the C $\alpha$  of sGly10. The side chains of Lys57 and Arg314 are positioned on either side of Trp332 and support its orientation in the binding site. Arg314 also forms a hydrogen bond with Trp332, and Lys57 with the nitrogen of Gln75, further stabilizing this interaction surface on G $\beta_1$ . Data from alanine scanning of the peptide (Scott, et al. (2001) supra; Goubaeva, et al. (2003) supra) validate these structural observations. Mutation of sIle8, sLeu9 or sGly10 to alanine increases the IC<sub>50</sub> for inhibition of PLC activation by 40-fold (5  $\mu$ M to 200  $\mu$ M), 60-fold and 12-fold, respectively (Scott, et al. (2001) supra). The same mutation of sLeu9 also blocks the ability of SIKK to enhance ERK1/2 phosphorylation in RASM cells (Goubaeva, et al. (2003) supra).

**[0090]** Mutation of amino acids in G $\beta_1$  that constitute the SIGK C-terminal binding surface caused a loss in affinity for the SIGK peptide, although to different extents. Mutation of Leu117, Met188, or Trp332 to alanine nearly abrogated SIKK binding; mutants of Lys57, Tyr59, Met101, and Arg314 had more modest effects (Table 6 and Table 8). The Trp99 mutation resulted in a 4-fold decrease in affinity. A summary of all the G $\beta_1$  mutations (i.e., conversions to alanine) presented herein and their effects on SIGK binding affinity is listed in Table 8.

TABLE 8

Loss in Affinity for SIGK Peptide					
	75-100%	50-75%	25-50%	0-25%	No Effect
G $\beta_1$ Residue	Lys57 Tyr59 Leu117 Tyr145 Asp186 Met188 Asn230 Trp332	Met101 Arg314	Trp99 Asn246	His311	His62 Phe292

**[0091]** Considering all of the data for the N-terminal and C-terminal SIGK binding interfaces, seven of the fifteen residues of the SIGK peptide and ten of the twelve G $\beta$  residues tested contribute significant binding energy to the interface, in good correlation with the structural model.

**[0092]** The binding surface of G $\beta_1$  in the G $\beta_1\gamma_2$ \*SIGK complex is not significantly changed upon SIGK binding. The RMSD between the core residues of G $\beta_1$  in the G $\beta_3\gamma_2$ \*SIGK complex and that in the uncomplexed G $\beta_1\gamma_1$  heterodimer (1TBG (Sondek, et al. (1996) *Nature* 379:369-74); Val40-Asn340, C $\alpha$  only) is 0.88 Å. However, the side chains of Trp99, Tyr59, Asp228, Leu117 and Met101 rotate to accommodate SIGK such that atoms within these residues undergo maximum displacements of 4.0 Å, 3.6 Å, 2.9 Å, 2.8 Å and 2.3 Å, respectively, relative to their positions in uncomplexed G $\beta_1$ . The B factors for residues in the SIGK binding surface are close to the overall average for the complex. However, the B factor for Trp99 is reduced two-fold upon binding to SIGK, as indicated by comparison of normalized B factors of the respective structures. In this analysis, there are no large con-

formational changes or disorder to order transitions in G $\beta$  upon SIGK binding. The SIGK•G $\beta_1\gamma_2$  complex may be compared to those of five G $\beta_1\gamma_2$  complexes with protein targets: the G $\beta_1\gamma_2$ •G $\alpha_{t1}$  heterotrimer (1GG2) (Wall, et al. (1995) supra; Wall, et al. (1998) supra) and the G $\beta_1\gamma_1$ •G $\alpha_{t1}$  heterotrimer (1GOT) (Lambright, et al. (1996) supra), the G $\beta_1\gamma_1$ •phosducin complex (1AOR and 2TRC) (Loew, et al. (1998) supra; Gaudet, et al. (1996) supra), and the G $\beta_1\gamma_2$ •GRK2 complex (1OMW) (Lodowski, et al. (2003) supra). Superposition of the G $\beta_1\gamma_2$ •SIGK complex with each of these structures yields average RMS deviations for G $\beta_1$  residues 40-340 of less than 1.0 Å (C $\alpha$  only). With the exception of a few residues involved in the G $\beta_1\gamma_1$ •phosducin complex, the G $\beta\gamma$  heterodimer does not undergo significant structural rearrangement in order to bind protein targets, nor does it in the G $\beta_1\gamma_2$ •SIGK structure.

## EXAMPLE 7

Measurement of  $\alpha$ - $\beta\gamma$  Interactions Via Flow Cytometry

**[0093]** Fluorescein-labeled G $\alpha_{t1}$  (F $\alpha_{t1}$ ) was prepared in accordance with standard methods (Sarvazyan, et al. (1998) supra). Assays were used to determine peptide effects on G $\alpha$ -G $\beta\gamma$  interactions included competition and dissociation assays (Ghosh, et al. (2003) supra). Briefly, for competition-based assays, 100 pM F $\alpha_{t1}$  and indicated concentrations of peptides were added to 50 pM b-G $\beta_1\gamma_2$  immobilized on 10<sup>5</sup> beads per mL and incubated at room temperature for 30 minutes to reach equilibrium. The bead-associated fluorescence was then recorded in a BD Biosciences FACSCALIBUR™ flow cytometer. Data was corrected for background fluorescence and fit with a sigmoid dose response curve using Graph Pad Prism 4. To measure dissociation of F $\alpha_{t1}$  from b-G $\beta_1\gamma_2$ , 100 pM of F $\alpha_{t1}$  was incubated with 50 pM immobilized b-G $\beta_1\gamma_2$  at room temperature for 15-20 minutes. The fluorescence of bound F $\alpha_{t1}$  subunit was measured, followed by the addition of a 200-fold excess of unlabeled G $\alpha_{t1}$  or peptides and the amount of F $\alpha_{t1}$  remaining bound to the beads was measured at the indicated times.

## EXAMPLE 8

## Molecular Recognition at the Protein Interaction Site

**[0094]** Having demonstrated that the interface for SIGK peptide binding was divided into two broad interactions; a C-terminal binding interface, which contacts the hydrophobic core of the peptide (amino acids 8-10, Ile-Leu-Gly), and an N-terminal interface, which associates with the N-terminus (Lys4 primarily) of the peptide, the molecular basis for

recognition of the peptide was determined. Accordingly, amino acids of the common binding surface of G $\beta_1$  were individually alanine substituted to determine which amino acids were most critical for the interaction of G $\beta_1\gamma_2$  with nine different SIGK peptide derivatives (Table 9).

TABLE 9

Phage Name	Sequence*	SEQ ID NO:	Group
3.14	SIGK <u>AL</u> FILGYPDYD	5	I
2F	LCSKAYLLLGQTC	6	
C1	SCRK <u>TK</u> AQILLAPCT	7	
C14	WCPPK <u>AM</u> TQLGKAC	8	II
3C	SCGHGL <u>KV</u> QSTIGACA	9	
C4	SCEK <u>RY</u> GIEFCT	10	III
C5	SCEKRLG <u>V</u> RSTCT	11	
C8	SCAR <u>FF</u> GTGCT	12	
C2	WCPPK <u>LE</u> QWYDGCA	13	IV

\*Underlined residues denote the lysine residue contacting the N-terminus, and the hydrophobic core residues.

**[0095]** The nine peptides were selected to represent the different consensus groups of peptides previously identified (See Scott et al. (2001) supra; Table 9) and to compare binding characteristics within and between consensus groups. Binding of phage displaying these peptides to wild-type G $\beta_1\gamma_2$  gave ELISA signals that were different, but fell within a similar range (25 to 100% binding relative to phage 3.14). As disclosed herein, the binding signal obtained in the ELISA assay was correlated to a loss in affinity by comparing the results to behavior of the peptide in a solution based assay. For example, a mutant displaying an 80% loss of binding in an ELISA had a corresponding 10-fold shift in peptide affinity in solution. For the purposes of present disclosure, any substitution that decreased the binding to less than 20% of the wild-type binding was considered to be a critical binding contact for that peptide. Data obtained from this analysis is presented in Table 10.

TABLE 10

Peptide	% of Wild-Type Signal						
	C-Terminal Interface				Shared		
	Trp332	Lys57	Tyr59	Trp99	Leu117	Met101	Met188
Group I							
3.14	7.1 ± 3.7	18.6 ± 4.6	24.7 ± 15.2	66.0 ± 7.7	2.1 ± 2.4	26.8 ± 12.5	2.5 ± 3.7
2F	-1.5 ± 3.6	-4.5 ± 6.2	-2.0 ± 9.5	32.6 ± 26.3	2.1 ± 5.5	6.0 ± 5.1	8.5 ± 5.2
C1	-0.3 ± 2.5	0.1 ± 1.6	0.3 ± 0.7	1.2 ± 2.7	5.2 ± 3.1	70.5 ± 35.3	4.0 ± 3.4

TABLE 10-continued

TABLE 10-continued							
Group II							
C14	1.6 ± 2.4	3.0 ± 5.0	3.6 ± 2.0	10.1 ± 3.3	3.8 ± 9.2	1.1 ± 4.9	9.9 ± 3.8
3C	-0.3 ± 1.7	3.6 ± 7.5	8.5 ± 6.4	-0.5 ± 5.9	10 ± 13.3	-4.2 ± 5.5	-5.7 ± 5.6
Group III							
C4	1.7 ± 3.0	-0.2 ± 1.9	7.6 ± 9.6	67.0 ± 15.2	18.4 ± 7.1	61.2 ± 30.9	127.5 ± 22.4
C5	3.2 ± 3.7	5.6 ± 5.3	73.8 ± 16.6	39.0 ± 3.8	28.5 ± 5.2	47.8 ± 18.9	97.2 ± 14.2
C8	0.7 ± 2.4	14.2 ± 9.8	4.0 ± 6.2	-0.8 ± 2.7	24.7 ± 12.5	23.6 ± 8.5	122.6 ± 26.2
Group IV							
C2	4.7 ± 6.2	-1.2 ± 4.5	-1.7 ± 4.8	-1.0 ± 5.1	1.5 ± 5.5	157.1 ± 51.5	-0.7 ± 2.5
% of Wild-Type Signal							
Peptide	N-Terminal Interface				Indirect		
	Asn230	Asp246	Tyr145	Asp186	His311	Arg314	
Group I							
3.14	22.4 ± 4.2	66.5 ± 7.5	0.8 ± 0.9	14.4 ± 13.4	93.4 ± 21.5	50.2 ± 5.0	
2F	27.6 ± 19.1	0.6 ± 2.5	0.1 ± 6.5	2.4 ± 3.5	23.6 ± 46.0	2.4 ± 3.9	
C1	19.8 ± 12.3	2.3 ± 3.0	88.0 ± 29.9	1.4 ± 1.7	3.0 ± 4.0	2.8 ± 1.6	
Group II							
C14	60.0 ± 26.5	6.3 ± 13.9	1.9 ± 5.9	3.6 ± 1.9	6.1 ± 3.4	3.9 ± 7.9	
3C	4.1 ± 4.4	2.0 ± 2.7	2.7 ± 10.5	35.0 ± 17.2	30.5 ± 18.9	8.3 ± 3.6	
Group III							
C4	11.5 ± 6.0	35.8 ± 7.4	4.4 ± 3.8	51.3 ± 15.0	36.5 ± 8.3	1.4 ± 1.0	
C5	33.5 ± 7.2	56.3 ± 4.1	16.7 ± 4.8	45.7 ± 5.2	58.7 ± 14.4	76.5 ± 6.7	
C8	74.8 ± 14.8	60.8 ± 14.4	17.5 ± 7.8	124.9 ± 29.1	51.6 ± 13.2	20.8 ± 11.1	
Group IV							
C2	0.0 ± 3.3	5.9 ± 5.7	4.5 ± 8.1	267.2 ± 40.6	11.7 ± 8.0	1.3 ± 3.1	

Wild-type or alanine-substituted biotinylated Gβ<sub>1</sub>γ<sub>2</sub> subunits were immobilized on a streptavidin-coated 96-well plate, followed by the addition of phage. Phage binding was assessed as described herein. Data was corrected for non-specific binding of phage to the plate and is represented as a percent wild-type binding. Data shown are mean ± SD of duplicate determinations from three independent experiments.

**[0096]** Unexpectedly, each of the peptides utilized unique combinations of amino acids within the SIGK binding surface for its particular interaction. A dominant feature amongst the peptides was a strong requirement for Trp332, within the C-terminal interface. Lys57, Tyr59, Leu117, also within this interface, generally contributed significantly to binding the peptides, though there were cases where their effects were not absolutely required. The remainder of the amino acids had more variable effects on binding of each peptide. For example, SIGK has a minimal requirement for Trp99 while Ser-Cys-Lys-Arg-Thr-Lys-Ala-Gln-Ile-Leu-Leu-Ala-Pro-Cys-Thr (C1; SEQ ID NO:7) absolutely requires Trp99 for binding. The reverse is true for Tyr145 where SIGK binding has an absolute requirement for Tyr145 and Ser-Cys-Lys-Arg-Thr-Lys-Ala-Gln-Ile-Leu-Leu-Ala-Pro-Cys-Thr (C1; SEQ ID NO:7) binding is not affected by this mutation.

**[0097]** The N-terminus of SIGK interacts with the GP subunit through two main contacts: sSer1 interactions with βAsp186 and βTyr145 residues, and sLys4 interactions with βMet188 through a Van der Waals interaction and βAsn230, βAsp246 and βAsp228 through hydrogen bonded or charged interactions. In the expression system utilized herein, Asp228Ala and Asp246Ala did not dimerize with gamma and could not be purified; however, Asp246Ser was expressed and purified. In general, peptides in groups I, II and IV have a substantial requirement for binding to the N-terminal region, reflected by an almost complete loss of binding to the Met188Ala and Asp246Ser (except SIGK) mutants and various requirements for Asn230.

**[0098]** Peptides in groups I, II and IV have a conserved motif where a lysine is spaced three amino acids away from a hydrophobic core motif (see Table 9). This motif in SIGK provides the appropriate spacing in a single alpha-helical turn between the lysine that interacts with the N-terminal binding surface and the Ile-Leu-Gly motif that interacts with the C-terminus. It is believed that some of the other peptides adopt a similar α-helical structure that may make this spacing critical. The peptides in group III bind the C-terminal interaction region, but lack a requirement for Met188 and have minimal requirements for Asn230 and Asp246, indicating they do not use the N-terminal binding surface for their interaction with β.

**[0099]** Two amino acids that do not apparently bind directly to SIGK were also analyzed, Arg314 and His311. Replacement of Arg314 results in a modest decrease in SIGK binding; however, for other peptides, Arg314 is absolutely required indicating that they may directly interact with this amino acid. His311 lies well outside the SIGK peptide binding site but was mutated because of its potential involvement in a conformation change in βγ subunits (Gaudet, et al. (1996) supra; Loew, et al. (1998) supra). The imidazole side chain of His311 is 13 Å from the guanido nitrogen of Arg314, the closest amino acid that apparently interacts with any of the peptides. It is unlikely that His311 could directly interact with amino acids from the phage display-derived peptides. Nevertheless, mutation of His311 to alanine affected binding of

various peptides to varying extents. Peptides whose binding was affected by His311A also required Arg314 for binding, an effect possibly due to an alteration in the position of Arg314.

**[0100]** It has been demonstrated that two peptides predicted to bind at the  $G\alpha$ - $G\beta\gamma$  interface,  $\beta$ ARK-ct peptide (amino acids 643-670) and QEHA, blocked heterotrimer formation but could not promote heterotrimer dissociation (Ghosh, et al. (2003) supra). The crystal structure of the GRK2 ( $\beta$ ARK)- $G\beta\gamma$  complex reveals that the surface interacting with the  $\beta$ ARK-ct peptide partially overlaps with the SIGK and  $G\alpha$ -switch II binding site (Lambright, et al. (1996) supra; Wall, et al. (1995) supra; Lodowski, et al. (2003) supra). In particular, amino acids Trp99, Trp332, and Try59 within the hydrophobic pocket are common interaction sites in all three structures. The SIGK peptide and  $\alpha$  switch II have a lysine residue occupying nearly identical positions on  $G\beta$ . Although the  $\beta$ ARK-ct peptide has a lysine residue in a similar position, the geometry and nature of the interaction is different.  $\beta$ ARK interacts only with Asp228 whereas SIGK and  $G\alpha$  interact with Asp228, Asp246, Asn230 and Met188. Based on this difference, it was determined whether the specific interactions of SIGK at this interface were critical for promoting dissociation.

**[0101]** To examine subunit dissociation, the SCAR peptide, another peptide derived from the phage display screen, was used. Amino acids within the N-terminal interaction interface, Asn230, Asp246 and Met188, contacting sLys4 of SIGK, are not important for binding SCAR. SCAR lacks a lysine residue with the correct positioning relative to the hydrophobic core motif to reach the lysine-binding N-terminal surface (Table 9). Therefore, SCAR would not be able to promote subunit dissociation. Both SIGK and SCAR can compete with  $G\alpha$ , for binding to  $G\beta_1\gamma_2$ , with  $IC_{50}$ 's of 0.5 and 1.7  $\mu$ M, respectively. However, unlike the SIGK peptide, saturating concentrations of SCAR peptide could not promote dissociation of a preformed heterotrimer. Concentrations of up to 160  $\mu$ M SCAR, (four times the saturating concentration) did not cause dissociation. The inability of SCAR to promote heterotrimer dissociation was not due to its lower binding affinity since SIRK has a similar affinity and promotes dissociation. These results indicate that peptide binding to the N-terminal interface is necessary for acceleration of heterotrimer dissociation.

**[0102]** To more directly assess the importance of peptide binding to the N-terminal peptide binding interface, the sLys4 residue of SIRK was mutated to alanine, eliminating the key contact to the N-terminal binding pocket. This peptide had a markedly lower affinity than SIRK ( $IC_{50}$ =60  $\mu$ M vs 1.4  $\mu$ M) for blocking  $G\alpha$ - $G\beta\gamma$  interactions; however, at high concentrations, it blocked to levels near that of SIRK. Despite blocking  $G\alpha$ - $G\beta\gamma$  interactions, SIRK(Lys4Ala) failed to accelerate heterotrimer dissociation. The apparent off-rate of  $F\alpha_{i1}$  appears slower for SIRK(Lys4Ala) relative to the intrinsic dissociation rate. This could be because SIRK(Lys4Ala) is low affinity blocker, and is not effective at preventing rebinding of  $F\alpha_{i1}$ . To confirm that the low affinity of SIRK(Lys4Ala) was not responsible for the inability to accelerate dissociation, a peptide with comparable affinity to SIRK(Lys4Ala), SIRK(Gly10Ala) ( $IC_{50}$ ~80  $\mu$ M), was tested. This peptide has Lys4 but Ala is substituted for Gly at position 10, thus SIRK(Gly10Ala) retains binding to the N-terminal interface but has a reduced affinity due to decreased interactions with the C-terminal region. SIRK(Gly10Ala) blocked heterotrimer

formation at high peptide concentrations and despite having a low affinity for  $G\beta\gamma$ , could still accelerate heterotrimer dissociation.

**[0103]** SIGK binds to  $G\beta_1$  at a region occupied by the switch II domain of  $G\alpha$  subunits in the heterotrimer. The crystal structure of the heterotrimer reveals the switch interface (composed of switch I and switch II) of  $G\alpha$  buries approximately 1,800  $\text{\AA}$  of  $G\beta$  through numerous contacts (Lambright, et al. (1996) supra; Wall, et al. (1995) supra); however, the effects of mutations of  $\beta$  subunit amino acids at this interface on  $\alpha$  subunit binding have not been measured in direct binding assays near the  $K_d$  for  $G\alpha$ - $G\beta\gamma$  interactions. Switch I and switch II undergo large conformational changes upon GTP binding and it is thought these changes mediate heterotrimer dissociation.

**[0104]**  $G\beta_1$  subunit mutants disclosed herein were isolated from insect cells as a complex with  $G\gamma_2$  and hexa-histidine-tagged  $G\alpha_{i1}$  indicating that many of these contacts between the subunits predicted from the crystal structures were not individually critical for  $G\alpha$  subunit binding. To determine which amino acids were contributing to the ability of peptides to enhance dissociation rate constants, the dissociation rate constant ( $k_{off}$ ) for  $F\alpha_{i1}$  from each of the individually substituted  $b$ - $\beta_1\gamma_2$  mutants was measured. The intrinsic off-rate for wild-type was 0.123 s<sup>-1</sup>, corresponding well with previous measurements (Sarvazyan, et al. (1998) *J. Biol. Chem.* 273: 7934-7940). Data from all of these mutants are shown in Table 11.

TABLE 11

Mutation	$k_{off}$ **
Wild-Type	0.123 ± 0.0429 min <sup>-1</sup>
Lys57Ala	0.144 ± 0.0441 min <sup>-1</sup>
Tyr59Ala	0.181 ± 0.0726 min <sup>-1</sup>
Trp99Ala	0.288 ± 0.0547 min <sup>-1</sup>
Met101Ala	0.114 ± 0.0175 min <sup>-1</sup>
Leu117Ala	0.361 ± 0.0258 min <sup>-1</sup>
Tyr145Ala	0.155 ± 0.0423 min <sup>-1</sup>
Asp186Ala	0.160 ± 0.0429 min <sup>-1</sup>
Met188Ala	0.122 ± 0.0380 min <sup>-1</sup>
Asn230Ala	0.148 ± 0.0488 min <sup>-1</sup>
Asp246Ser <sup>†</sup>	—
Arg314Ala	0.118 ± 0.0246 min <sup>-1</sup>
Trp332Ala	0.301 ± 0.0420 min <sup>-1</sup>

\*\*Mean ± SD from four independent experiments.

<sup>†</sup>Statistically significant as compared to wild-type ( $p < 0.05$ ) as determined by a one-way ANOVA followed by independent linear contrasts.

<sup>††</sup> $k_{off}$  could not be measured because significant stable binding of  $F\alpha_i$  was not detectable.

**[0105]** The results showed that of the 12 mutants tested, Trp99Ala, Leu117Ala, and Trp332Ala were statistically different from wild-type with relatively minor increases in  $k_{off}$ . On the other hand, Asp246Ser, despite being able to be purified based on 6His $G\alpha_i$  binding (although in low yield from a large culture), was unable to stably bind  $F\alpha_{i1}$  in the flow cytometry assay at the low concentrations used for this assay. This indicates that interactions with Asp246 are critical for stable  $G\alpha$  subunit interactions, while individual interactions in the primarily hydrophobic C-terminal interface are not as important.

#### EXAMPLE 9

##### Small Molecule Library Screen

**[0106]** A phage ELISA assay was used to determine whether small molecules identified in the computational

screen could interact with the G $\beta$  protein interaction surface. Phage displaying the SIGK peptide were used in accordance with established methods (Scott, et al. (2001) supra; Smrcka and Scott (2002) supra). The screen was based on a reduction in the optical density (OD) of wells containing G $\beta$  subunits and phage. In each plate, three wells contained positive controls for binding that included b- $\beta$  subunits, SIGK-phage, and the appropriate amount of vehicle. Three background wells contained no  $\beta$  subunits.

**[0107]** As disclosed herein, biotinylated G $\beta$  subunits were immobilized on the surface of a 96-well plate coated with streptavidin, phage displaying G $\beta$ -binding peptides were subsequently added and binding in the presence and absence of test compounds detected with an anti-phage antibody.

#### EXAMPLE 10

##### Inhibition of G $\beta$ Signaling in Neutrophils

**[0108]** Ca<sup>2+</sup> fluxes were measured using two 35 mL cultures of differentiated HL-60 neutrophil cultures (0.2 $\times$ 10<sup>6</sup>

cells/mL). Cells were cultured for three days with in DMSO (1.2%), washed in HSS and resuspended in 2 mL HBSS at a concentration of 7 $\times$ 10<sup>6</sup> cells/mL. Addition of DMSO to the growth medium induces differentiation of these cells into morphologically and functionally mature neutrophils (Collins, et al. (1978) *Proc. Natl. Acad. Sci. USA* 75:2458; Collins, et al. (1979) *J. Exp. Med.* 149:969). Neutrophils were pre-loaded with fura-2 (1  $\mu$ M), a fluorescent Ca<sup>2+</sup>-sensitive indicator (Suh, et al. (1996) *J. Biol. Chem.* 271:32753), for 45 minutes, washed with HBSS and resuspended in 2 mL of indicator-free HBSS. An 140  $\mu$ L aliquote of cells was added to a total of 2 mL HBSS. Fluorescence ratios were taken by dual excitation at 340 and 380 nm and emission at 510 nm. After a stable baseline was established, either DMSO or NSC119910 was added and incubated for 5 minutes. Subsequently, either fMLP or ATP agonists were added to activate release of Ca<sup>2+</sup> from intracellular stores.

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Leu Val Ser Gly Leu Glu Val Val Gly Arg Val Gln Met Arg Thr Arg  
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Arg Thr Leu Arg Gly His Leu Ala Lys Ile Tyr Ala Met His Trp Ala  
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Thr Asp Ser Lys Leu Leu Val Ser Ala Ser Gln Asp Gly Lys Leu Ile  
 65                    70                    75                    80

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 Arg Glu Gly Asn Val Lys Val Ser Arg Glu Leu Ser Ala His Thr Gly  
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 Tyr Leu Ser Cys Cys Arg Phe Leu Asp Asp Asn Asn Ile Val Thr Ser  
 145 150 155 160  
 Ser Gly Asp Thr Thr Cys Ala Leu Trp Asp Ile Glu Thr Gly Gln Gln  
 165 170 175  
 Lys Thr Val Phe Val Gly His Thr Gly Asp Cys Met Ser Leu Ala Val  
 180 185 190  
 Ser Pro Asp Tyr Lys Leu Phe Ile Ser Gly Ala Cys Asp Ala Ser Ala  
 195 200 205  
 Lys Leu Trp Asp Val Arg Glu Gly Thr Cys Arg Gln Thr Phe Thr Gly  
 210 215 220  
 His Glu Ser Asp Ile Asn Ala Ile Cys Phe Phe Pro Asn Gly Glu Ala  
 225 230 235 240  
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 245 250 255  
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 260 265 270  
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 Tyr Asp Asp Phe Asn Cys Asn Val Trp Asp Ser Leu Lys Cys Glu Arg  
 290 295 300  
 Val Gly Val Leu Ser Gly His Asp Asn Arg Val Ser Cys Leu Gly Val  
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What is claimed is:

1. A method for identifying an agent that modulates at least one activity of a G protein comprising contacting a G protein  $\beta$  subunit with a test agent and determining whether the agent interacts with at least one amino acid residue of the protein interaction site of the  $\beta$  subunit thereby identifying an agent that modulates at least one activity of the G protein.

2. An agent identified by the method of claim 1.

3. A method for identifying an agent that binds at least one amino acid residue of the protein interaction site of the  $\beta$  subunit comprising

contacting a G protein  $\beta$  subunit with a test agent in the presence of a peptide that binds at least one amino acid residue of the protein interaction site of  $\beta$  subunit; and determining whether the agent inhibits the binding of the peptide to the at least one amino acid residue of the protein interaction site of the  $\beta$  subunit thereby identifying an agent that binds at least one amino acid residue of the protein interaction site of the  $\beta$  subunit.

4. An agent identified by the method of claim 3.

5. A kit for identifying an agent that binds at least one amino acid residue of the protein interaction site of the  $\beta$  subunit, said kit comprising a SIGK peptide or SIGK peptide derivative.

6. A method for modulating at least one activity of a G protein comprising contacting a G protein with an effective amount of an agent that interacts with at least one amino acid residue of the protein interaction site of the G protein  $\beta$  subunit so that at least one activity of the G protein is modulated.

7. A method for preventing or treating a disease or condition involving at least one G protein  $\beta\gamma$  subunit activity comprising administering to a patient having or at risk of having a disease or condition involving at least one G protein  $\beta\gamma$  subunit activity an effective amount of an agent that interacts with at least one amino acid residue of the protein interaction site of the G protein  $\beta$  subunit so that the at least one activity of the G protein is modulated thereby preventing or treating the disease or condition involving the at least one G protein  $\beta\gamma$  subunit activity.

\* \* \* \* \*