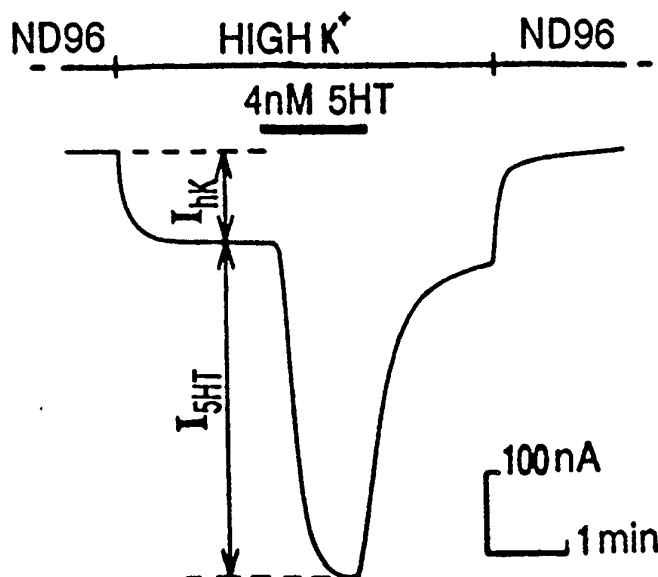




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(54) Title: DNA ENCODING INWARD RECTIFIER, G-PROTEIN ACTIVATED, MAMMALIAN, POTASSIUM KGA CHANNEL AND USES THEREOF



(57) Abstract

Isolated nucleic acid molecules which encode inward rectifier, G-protein activated, mammalian potassium KGA channels are disclosed. Also provided are related nucleic acid probes, vectors, and recombinant expression systems for the KGA potassium channels.

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DNA ENCODING INWARD RECTIFIER, G-PROTEIN
ACTIVATED, MAMMALIAN, POTASSIUM KGA CHANNEL
AND USES THEREOF

The invention disclosed herein was made with U.S. Government
5 support under USPHS grants GM29836 and MH49176. Accordingly,
the the U.S. government has certain rights in this
invention.

Background of the Invention

10 Throughout this application various publications are
referenced by their reference number within parentheses.
Full citations for these publications may be found at the
end of the specification immediately preceding the sequence
listing. The disclosures of these publications in their
15 entireties are hereby incorporated by reference into this
application in order to more fully describe the state of the
art to which this invention pertains.

Parasympathetic regulation of the rate of heart contraction
is exerted through the release of acetylcholine (ACh), which
20 opens a K⁺ channel in the atrium and thus slows the rate of
depolarization that leads to initiation of the action
potential (1,2). The coupling between binding of ACh to a
muscarinic receptor and opening of the K⁺ channel occurs via
a pertussis toxin (PTX)-sensitive heterotrimeric G-protein,
25 G_k(3-5), probably belonging to the G_i family (6,7).
Activation of this G-protein-activated K⁺ channel by G_k does
not require cytoplasmic intermediates (reviewed in refs.
8,9). However, a long-standing controversy exists as to

which G-protein subunit couples to the KG channel. Purified $\beta\gamma$ subunit complex (10,11) and α subunits of G_i family (6,7,12) activate the KG channel in cell free, inside-out patches of atrial myocytes. Activation by the α subunits
5 occurs at lower concentrations than that by $\beta\gamma$, but seems to be less efficient (13); the relative physiological importance of each pathway, as well as of possible involvement of the arachidonic acid pathway (14), is unclear.

10 A channel similar or identical to the ACh-operated KG can be activated in the atrium by adenosine (15), ATP (16), and epinephrine (17), probably also via a G-protein pathway. Furthermore, in nerve cells various 7-helix receptors such as serotonin 5HT_{1A}, δ -opioid, GABA_B, somatostatin, etc.,
15 couple to similar K⁺ channels, probably through direct activation by G-proteins (18-22). The similarity of the channels and of the signaling pathways in atrium and some nerve cell preparations was strengthened by the demonstration of the coupling of a neuronal 5HT_{1A} receptor
20 (5HT_{1A}-R), transiently expressed in atrial myocytes, to the atrial KG (23).

By electrophysiological and pharmacological criteria, the atrial KGA channel belongs to a family of inward rectifiers that conduct K⁺ much better in the inward than the outward
25 direction, are blocked by extracellular Na⁺, Cs⁺ and Ba²⁺, and are believed to possess a single-file pore with several permeant and blocking ion binding sites (24). Many inward rectifiers are not activated by transmitters or voltage but seem to be constitutively active. Inward rectification of
30 the atrial KGA channel is due to block of K⁺ efflux by intracellular Mg²⁺ (25), but for some channels of this family inward rectification may not depend on Mg²⁺ block (26,27). The molecular structures of atrial and neuronal KGs are unknown. Inwardly rectifying K⁺ channels structurally
35 similar to voltage-activated K⁺ channels have been cloned from plant cells (28,29). Recently, the primary structures

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of two mammalian inward rectifier channels have been elucidated by molecular cloning of their cDNAs via expression in *Xenopus* oocytes: an ATP-regulated K⁺ channel from kidney, ROMK1 (30), and an inward rectifier from a macrophage cell line, IRK1 (31). Both appear to belong to a new superfamily of K⁺ channels, with only two transmembrane domains per subunit and a pore region homologous to that of K⁺, Ca²⁺ and Na⁺ voltage-dependent channels (see ref. 32). It has been hypothesized that the structure of G-protein activated inward rectifying K⁺ channels should be similar to that of ROMK1 and IRK1 (31). Cloning of the atrial KGA channel and its expression in a heterologous system would be of importance not only for testing this hypothesis, but also because it will allow an as yet unexplored molecular approach to investigation of the mechanisms of direct G-protein-ion channel coupling. As a first step to cloning of the atrial KGA channel we have expressed it in *Xenopus* oocyte injected with atrial RNA and characterized the macroscopic current properties, including a preliminary characterization of G-protein coupling. We cloned the atrial KGA from a cDNA library derived from mRNA extracted from the heart of a 19 day old rat.

Summary of the Invention

This invention provides isolated nucleic acid molecules which encode inward rectifier, G-protein activated, mammalian, potassium KGA channel.

This invention also provides a nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with the above nucleic acid molecule.

This invention further provides a vector comprising the isolated nucleic acid molecules encoding an inward rectifier, G-protein activated, mammalian, potassium KGA channel.

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This invention provides a host vector system for the production of a polypeptide having the biological activity of KGA channel which comprises the above vector in a suitable host.

5 This invention also provides a method for isolating from a sample a nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel in a sample which comprises: (a) isolating the nucleic acids from the sample; (b) contacting the isolated nucleic acids with the molecule
10 of at least 15 nucleotides capable of specifically hybridizing with the above nucleic acid molecule which encode inward rectifier, G-protein activated, mammalian, potassium KGA channel under the conditions permitting complex formation between the nucleic acid molecule encoding
15 an inward rectifier, G-protein activated, potassium channel and the nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with the above nucleic acid molecule which encode inward rectifier, G-protein activated, mammalian, potassium KGA channel; (c) isolating
20 the complex formed; and (d) separating the nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel from the complex, thereby isolating the nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel.

25 Brief Description of Figures

Figure 1. Inward currents evoked by high K^+ , 5HT and ACh in RNA-injected oocytes. (A) I_{hk} and I_{5HT} in an oocyte injected with atrial RNA + 5HT1A-R RNA. Holding potential in this and all following Figures was -80mV. (B) Inward currents
30 evoked by ACh (AcCho) and 5HT in a single oocyte in hK solution. (C) The dependence of I_{5HT} amplitude on 5HT concentration in oocytes of one frog. In each oocyte, the response to one 5HT concentration was tested. Data represent mean $\pm$ SEM in 4-6 cells at each concentration.

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- Figure 2. I_{hK} and I_{5HT} are inwardly rectifying K^+ currents. (A) Currents evoked by voltage steps from the holding potential of -80 mV to voltages between -140 and 40 mV in 20 mV steps in ND96 (a), hK (b), hK in the presence of 5HT (c). Net I_{5HT} (d) was obtained by digital subtraction of (b) from (c). (B) Current-voltage relations of the total membrane current in a representative oocyte in NG 96 (2 mM [Kout]; $\square$), in 25 mM [K⁺out] ($\blacklozenge$); in 75 mM [Kout] (o, and in hK (96 mM [Kout]; $\blacktriangle$). (C) Current-voltage relation of the net I_{5HT} in the same oocyte as in (B) in 25 mM [Kout] ($\blacklozenge$), 75 mM [Kout] (o), and 96 mM [Kout] ($\blacktriangle$). (D) The dependence of the reversal potentials of total membrane current ($\blacktriangle$) and of I_{5HT} ($\bullet$) on [Kout]. The straight lines represent least square fits to data (mean $\pm$ SEM, n=3 for each point).
- 15 Figure 3. Ba^{2+} block of I_{hK} and I_{5HT} . (A-C), records taken from the same oocyte at 10 min intervals. Between the records, the cell was bathed in ND96. 5HT concentration was 4 nM. Note that in (B) 300 μ M Ba^{2+} reduces I_{hK} and almost completely blocks I_{5HT} . Ba^{2+} and 5HT were washed out simultaneously, and this resulted in an inward current "tail". (D) dose dependence of Ba^{2+} inhibition of I_{hK} in native oocytes (o), I_{hK} in RNA-injected oocytes ($\bullet$), I_{5HT} in RNA-injected oocytes (∇). Data are mean $\pm$ SEM, n=3 to 7 for each point.
- 25 Figure 4. I_{5HT} is mediated by activation of a G-protein. (A) The effect of PTX treatment (500 ng/ml, 20-26 h) on I_{hK} and I_{5HT} . The cells were injected with 120 ng/oocyte total atrial RNA, 11 ng/oocyte 5HT1A-R RNA, and, where indicated, with 11 ng/oocyte $G_{i2}\alpha$ RNA. (B) GDP- β -S injection inhibits I_{5HT} but not I_{hK} in an oocyte injected with atrial + 5HT1A-R RNAs. 5HT concentration was 0.4 μ M. A small outward current deflection (denoted by $\star$) upon washout of 5HT was caused by an inadvertent perfusion of ND96 for a few seconds.
- 30

Figure 5. Nucleotide and deduced amino acid sequence encoding the inward rectifier, G-protein associated, mammalian, potassium KGA channel. Numbers in the right hand margin correlate to nucleotide position and numbers below 5 the amino acid sequence correlate with amino acid position.

Detailed Description of the Invention

This invention provides isolated nucleic acid molecules which encode inward rectifier, G-protein activated, mammalian, potassium KGA channel. As used herein, the term
10 inward rectifier, G-protein activated, mammalian, potassium KGA channel encompasses any amino acid sequence, polypeptide or protein having biological activities provided by the inward rectifier, G-protein activated, mammalian, potassium KGA channel. Furthermore the G-protein activation can be
15 either directly or indirectly, and involve one or more G-proteins.

In one embodiment of this invention, the isolated nucleic acid molecules described hereinabove are DNA. In other embodiments of this invention, the isolated nucleic acid
20 molecules described hereinabove are cDNA, genomic DNA or RNA. In the preferred embodiment of this invention, the isolated nucleic acid molecule is a cDNA as shown in sequence ID number 43717.APP.

This invention also encompasses DNAs and cDNAs which encode
25 amino acid sequences which differ from those of inward rectifier, G-protein activated, mammalian, potassium KGA channel, but which should not produce functional changes in the KGA channel. This invention also encompasses nucleic acid molecules of at least 15 nucleotides capable of
30 specifically hybridizing with the nucleic acid molecule which encode inward rectifier, G-protein activated, mammalian, potassium KGA channel. Hybridization methods are well known to those of skill in the art.

The DNA molecules of the subject invention also include DNA molecules coding for polypeptide analog, fragments or derivatives of substantially similar polypeptides which differ for naturally-occurring forms in terms of the identity of location of one or more amino acid residues (deletion analogs containing less than all of the residues specified for the protein, substitution analogs wherein one or more residues are replaced by other residues and addition analog wherein one or more amino acid residues is added to a terminal or medial portion of the polypeptides) and which share some or all properties of naturally- occurring forms. These sequences include: the incorporation of codons preferred for expressions by selected non-mammalian host; the provision of sites for cleavage by restriction endonuclease enzymes; the addition of promoters operatively linked to enhance RNA transcription; and the provision of additional initial, terminal or intermediate DNA sequences that facilitate construction of readily expressed vectors.

The nucleic acid molecule described and claimed herein is useful for the information which it provides concerning the amino acid sequence of the polypeptide and as products for the large scale synthesis of the polypeptide by a variety of recombinant techniques. The nucleic acid molecule is useful for generating new cloning and expression vectors, transformed and transfected procaryotic and eucaryotic host cells, and new and useful methods for cultured growth of such host cells capable of expressing the inward rectifier, G-protein activated, mammalian, KGA potassium channel and related polypeptides with biological activity of the KGA channel. Capable hosts for such host vector systems may include but are not limited to a bacterial cell, an insect cell, a mammalian cell, and a Xenopus oocyte.

The isolated RNA molecule described and claimed herein is useful for the information it provides concerning the amino acid sequence of the polypeptide and as a product for synthesis of the polypeptide by injecting the RNA molecules

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into *Xenopus* oocytes and culturing the oocytes under conditions that are well known to an ordinary artisan.

Moreover, the isolated nucleic acid molecules are useful for the development of probes to screen for and isolate related
5 molecules from nucleic acid libraries other tissues, or organisms.

Inward rectifier, G-protein activated, mammalian, potassium KGA channel may be produced by a variety of vertebrate animals. In an embodiment, a rat inward rectifier, G-
10 protein activated, mammalian, potassium KGA channel is isolated. A sequence of the DNA of rat inward rectifier, G-protein activated, mammalian, potassium KGA channel is shown in Figure 5.

The resulting plasmid, pBSIIKS(-)KGA, encoding the rat
15 inward rectifier, G-protein activated, mammalian, potassium KGA channel was deposited on May 17, 1993 with the American Type Culture Collection (ATCC), 12301 Parklawn Drive, Rockville, Maryland 20852, U.S.A., under the provisions of the Budapest Treaty for the International Recognition of the
20 Deposition of Microorganism for the Purposes of Patent Procedure. Plasmid, pBSIIKS(-)KGA, was accorded ATCC accession number 75469.

Throughout this application, references to specific nucleotides are to nucleotides present on the coding strand
25 of the nucleic acid. The following standard abbreviations are used throughout the specification to indicate specific nucleotides:

C = cytosine
T = thymidine

A = adenosine
G = guanosine

30 For the purpose of illustration only, applicants used a cDNA plasmid library derived from 19-day-old rat atrial mRNA. The DNA was synthesized from the mRNA by reverse

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transcriptase using a poly(dt) primer with a XhoI overhang and was methylated. Adapters with EcoRI sites were ligated to both ends and the cDNA was digested with XhoI. It was ligated into XhoI-EcoRI-digested pBluescriptII KS(-). The library was linearized and amplified by polymerase chain reaction of the cDNA using primers that were complementary to sequences flanking the cDNA insert. cRNA was synthesized *in vitro* from the T7 promoter using T7 RNA polymerase. The cRNA was microinjected into *Xenopus laevis* oocytes and electrophysiological recordings under conditions described in Experimental Materials and Methods determined identification of a inward rectifier, G-protein activated, mammalian, potassium KGA channel. Fewer and fewer CDNA clones from the library were used after identification of the KGA channel until the cDNA of the inward rectifier, G-protein activated, mammalian, potassium KGA channel was isolated.

This invention provides a nucleic acid probe comprising a nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with a sequence included within the sequence of a nucleic acid molecule encoding an inward rectifier, G-protein activated, mammalian, potassium KGA channel. As used herein, the phrase "specifically hybridizing" means the ability of a nucleic acid molecule to recognize a nucleic acid sequence complementary to its own and to form double-helical segments through hydrogen bonding between complementary base pairs. Nucleic acid probe technology is well known to those skill in the art who will readily appreciate that such probes may vary greatly in length and may be labeled with a detectable label, such as a radioisotope or fluorescent dye, to facilitate detection of the probe. DNA probe molecules may be produced by insertion of a DNA molecule which encodes inward rectifier, G-protein activated, mammalian potassium KGA channel into suitable vectors, such as plasmids, bacteriophages, or retroviral vectors followed by transforming into suitable host cells and harvesting of the DNA probes, using methods

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well known in the art. Alternatively, probes may be generated chemically from DNA synthesizers.

The probes are useful for 'in situ' hybridization to locate tissues which express this gene, or for other hybridization assays for the presence of this gene or its in RNA in various biological tissues.

Vectors which comprise the isolated nucleic acid molecule described hereinabove also are provided. Suitable vectors comprise, but are not limited to, a plasmid or a virus. These vectors may be transformed into a suitable host cell to form a host cell vector system for the production of a polypeptide having the biological activity of inward rectifier, G-protein activated, mammalian potassium KGA channel.

This invention further provides an isolated DNA or cDNA molecule described hereinabove wherein the host cell is selected from the group consisting of bacterial cells such as E. coli, yeast cells, fungal cells, insect cells and animal cells. Suitable animal cells include, but are not limited to Cos cells, HeLa cells, L(tk-), and various primary mammalian cells.

This invention provides a method for isolating from a sample a nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel using the probe generated from the rat inward rectifier, G-protein activated, mammalian, potassium KGA channel gene. For the human, inward rectifier, G-protein activated, mammalian, potassium KGA channel, it is conceivable that the degree of homology between rat and human could be considerable. Homology studies of the inward rectifier, G-protein activated, mammalian, potassium KGA channel using Genetics Computer Group Sequence Analysis Software, Version 7.2, revealed 55% identity with Human clone HHCMD37 (Genbank Accession # M78731). Human heart cDNA library and human

genomic library may be used for such screening. Duplicate filters of human libraries may be screened with radio labelled probe derived from the rat inward rectifier, G-protein activated, mammalian, potassium KGA channel DNA molecule. The filters containing the human libraries will be hybridized with the probe at low stringency (Sambrook, et al 1989) and positive clones identified.

This invention provides a method to identify and purify inward rectifier, G-protein activated, potassium channels.

10 A sample of nucleic acid molecules can be screened for nucleic acid molecules capable of supporting complex formations with an inward rectifier, G-protein activated, mammalian, KGA potassium channels nucleic acid molecule of at least 15 nucleotides under conditions well known in the art that cause complex formation between nucleic acids molecules. "Sample" as used herein includes but is not limited to genomic libraries, cDNA libraries, nucleic acid molecule extracts from tissue, or nucleic acid molecule extracts from cell culture. Conditions that pertain to

15 complex formation between nucleic acids are well understand by an ordinary skilled artisan and include but are not limited to suboptimal temperature, ionic concentration, and size of the nucleic acid molecule. After complex formation between the nucleic acid molecule encoding the inward

25 rectifier, G-protein activated, mammalian, KGA potassium channel and another nucleic acid, the other nucleic acid molecule can be isolated by methods known in the art.

This invention provides a method for isolating from a sample a nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel in a sample which

30 comprises: (a) isolating the nucleic acids from the sample; (b) contacting the isolated nucleic acids with the nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with the nucleic acid molecule of an isolated nucleic acid molecule encoding an inward

35 rectifier, G-protein activated, mammalian, potassium KGA

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channel under the conditions permitting complex formation between the nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel and the nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with the nucleic acid molecule of an isolated nucleic acid molecule encoding an inward rectifier, G-protein activated, mammalian, potassium KGA channel; (c) isolating the complex formed; and (d) separating the nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel from the complex, thereby isolating the nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel.

This invention further provides a method for isolating DNA encoding an inward rectifier, G-protein activated, potassium channel or a fragment thereof in a sample which comprises: (a) isolating the DNA from the sample; (b) denaturing the isolated DNA; (c) reannealing the denatured nucleic acids in the presence of two unique single stranded nucleic acid molecules of at least 15 nucleotides capable of specifically hybridizing with the nucleic acid molecule of the inward rectifier, G-protein associated, mammalian, potassium KGA channel that are complementary to nucleotide sequences on opposite strands of an isolated DNA molecule encoding an inward rectifier, G-protein activated, mammalian, potassium KGA channel; (d) polymerizing the reannealed nucleic acids with DNA polymerase under conditions that allow DNA polymerization; (e) denaturing the polymerized DNA in (d); (f) repeating steps (c) through (e) for more than 10 cycles; and (g) isolating the polymerization product in step (f). The term "unique" as used herein defines a nucleic acid molecule that does not contain known genomic repeated sequences, including but not limited to Alu sequences.

This invention provides a method for isolating DNA encoding an inward rectifier, G-protein activated, potassium channel or a fragment thereof in a sample which comprises: (a)

isolating the DNA from the sample; (b) denaturing the isolated DNA; (c) reannealing the denatured nucleic acids in the presence of a unique single stranded nucleic acid molecules of at least 15 nucleotides capable of specifically hybridizing with the nucleic acid molecule of the inward rectifier, G-protein associated, mammalian, potassium KGA channel that is complementary to nucleotide sequences of an isolated DNA molecule encoding an inward rectifier, G-protein activated, mammalian, potassium KGA channel and a single stranded nucleic acid molecule encoding a known genomic repeat sequence; (d) polymerizing the reannealed nucleic acids with DNA polymerase under conditions that allow DNA polymerization; (e) denaturing the polymerized DNA in (d); (f) repeating steps (c) through (e) for more than 10 cycles; and (g) isolating the polymerization product in step (f).

This invention provides the above method for isolating from a sample a nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel in a sample wherein, the nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with the nucleic acid molecule of an isolated nucleic acid molecule encoding an inward rectifier, G-protein activated, mammalian, potassium KGA channel is labelled with a detectable marker.

The invention provides the nucleic acid molecule isolated by the above method for isolating from a sample a nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel in a sample.

This invention provides a purified inward rectifier, G-protein activated, mammalian, potassium KGA channel.

This invention also provides the above-described purified channel having substantially the same amino acid sequence as the amino acid sequence shown in Figure 5.

This invention provides a protein encoded by the above-described isolated nucleic acid molecule.

This invention provides a method for determining whether an agent activates a KGA channel which comprises: (a) 5 contacting the host vector system of claim 10 with the agent under conditions permitting the KGA channel conductance to be affected by known ion channel agonists or intracellular second messenger agonists; and (b) detecting any change in KGA channel conductance, an increase in KGA channel 10 conductance indicating that the agent activates the KGA channel. The term "agent" as used herein describes any molecule, protein, or pharmaceutical with the capability of directly or indirectly altering ion channel conductance by affecting second messenger systems or the ion channel 15 directly. Agents include but are not limited to serotonin, neurotropin, enkephalins, dopamine, arachidonic acid, cholera toxin, and pertussis toxin. The term "activators" as used herein defines any agent which activates a G-protein associated receptor. The term "activates" as used herein is 20 applied to both G-protein associated receptors and ion channel conductance and in terms of G-protein associated receptors defines the state of the receptor wherein it initiates release of a G-protein subunit which in turn initiates a cellular response. In terms of the ion channel 25 conductance "activates" defines the state of the channel wherein the channel increases conductance. The term "deactivates" as used herein defines the state of the channel wherein the channel is initiated to decrease conductance or is incapable of conductance under conditions 30 when the channel normally conducts ions across a membrane.

This invention also provides the agent identified by the above method.

This invention provide a pharmaceutical composition 35 comprising an amount of the above agent effective to

increase KGA conductance and a pharmaceutical acceptable carrier.

This invention provides a method for determining whether an agent deactivates KGA channel conductance which comprises:

- 5 (a) contacting the host vector system for the production of a polypeptide having the biological activity of KGA channel which comprises the vector comprising the nucleic acid molecule encoding an inward rectifier, G-protein activated, mammalian, potassium KGA channel operatively linked to a
10 promoter of RNA transcription in a suitable host with the agent under conditions permitting the KGA channel conductance to be affected by known ion channel antagonists or intracellular second messenger system agonist; and
- (b) detecting any change in KGA channel conductance, a
15 decrease in KGA channel conductance indicating that the agent deactivates the KGA channel. The term "agonist" as used herein defines an agent that initiates activation of ion channel conductance or initiates activation of a second messenger system. The term "antagonist" as used herein
20 defines an agent initiates deactivation of ion channel conductance or initiates deactivation of a second messenger system.

This invention provides agents identified by the above method for determining whether an agent deactivates KGA
25 channel conductance.

This invention provides a pharmaceutical composition comprising an amount of the above agent effective to decrease KGA channel conductance and a pharmaceutical acceptable carrier.

- 30 This invention provides a method for identifying in a nucleic acid sample a nucleic acid molecule encoding a G-protein associated receptor which activates the inward rectifier, G-protein activated, mammalian, KGA potassium channel which comprises: (a)introducing nucleic acid

molecules of claim 1 and sample to a *Xenopus* oocyte under conditions permitting expression of both the receptor and the channel; (b) contacting the oocyte of step (a) with a panel of known G-protein associated receptor activators; and
5 (c) detecting any change in KGA channel conductance, an increase in KGA channel conductance indicating the identification of a G-protein associated receptor which activates the KGA channel.

This invention provides a method for isolating from a cDNA
10 expression library a G-protein associated receptor which activates the inward rectifier, G-protein activated, mammalian potassium KGA channel which comprises:

(a) isolating cDNA from a sample containing a number of clones of the cDNA expression library; (b) linearizing cDNA
15 sample if necessary; (c) transcribing the linearized cDNA; (d) isolating the RNA from the transcribed cDNA; (e) introducing the isolated RNA and nucleic acid molecules of claim 1 into a *Xenopus* oocyte under conditions permitting expression of the KGA channel and G-protein associated
20 receptor; (f) contacting the oocyte of step (e) with a panel of known G-protein associated receptor activators; (g) detecting change in KGA channel conductance; and (h) repeating steps (a) through (g) when an increase in KGA channel conductance is detected in step (g) using fewer cDNA
25 clones from the sample until isolation of a single cDNA clone encoding a G-protein associated receptor which activates the KGA channel.

The invention provides a cDNA encoding the G-protein associated receptor isolated in the above method for
30 isolating from a cDNA expression library a G-protein associated receptor which activates the inward rectifier, G-protein activated, mammalian potassium KGA channel.

The invention provides a G-protein associated receptor isolated in the above method for isolating from a cDNA
35 expression library a G-protein associated receptor which

activates the inward rectifier, G-protein activated, mammalian potassium KGA channel.

This invention provides a method for testing whether a G-protein associated receptor activates the inward rectifier, G-protein activated, mammalian, KGA potassium channel which comprises: (a) introducing a nucleic acid molecule of claim 1 and a nucleic acid molecule encoding the G-protein associated receptor to a *Xenopus* oocyte under conditions permitting expression of both the receptor and the channel; (b) contacting the oocyte of step (a) with a known G-protein associated receptor activator; and (c) detecting any change in KGA channel conductance, an increase in KGA channel conductance indicating that the G-protein associated receptor activates the KGA channel.

This invention provides a method for identifying in a nucleic acid sample a G-protein associated receptor capable of deactivating the inward rectifier, G-protein activated, mammalian KGA potassium channel comprising: (a) introducing nucleic acid molecule of claim 1, nucleic acid molecule of a G-protein associated receptor known to activate the KGA channel, and sample of isolated nucleic acids to a *Xenopus* oocyte under conditions permitting expression of the G-protein associated receptor that activates the KGA channel, the KGA channel and a known G-protein associated receptor; (b) contacting the oocyte of step (a) with a known G-protein associated receptor activator and a panel of known G-protein associated receptor activators; and (c) detecting any change in KGA channel conductance, a decrease in KGA channel conductance indicating the identification of an G-protein associated receptor capable of deactivating the KGA channel in the sample.

This invention provides a method for isolating from a cDNA expression library an G-protein associated receptor which deactivates the inward rectifier, G-protein activated, mammalian potassium KGA channel which comprises:

(a) isolating cDNA from a sample containing a number of clones of the cDNA expression library; (b) linearizing cDNA sample if necessary; (c) transcribing the linearized cDNA; (d) isolating the RNA from the transcribed cDNA; (e) introducing the isolated RNA, nucleic acid molecule encoding a known G-protein associated receptor which activates the KGA channel, and nucleic acid molecules of claim 1 into a *Xenopus* oocyte under conditions permitting expression of the KGA channel and both receptors; (f) contacting the oocyte of step (e) with a known G-protein associated receptor activator and a panel of known inhibitory G-protein associated activators; (g) detecting any change in KGA channel conductance,; and (h) repeating steps (a) through (g) when a decrease in KGA channel conductance is detected in step (g) using fewer number of cDNA clones from the sample until isolation of a single cDNA clone encoding an inhibitory G-protein associated receptor which deactivates the KGA channel.

The invention provides a cDNA encoding the G-protein associated receptor isolated by the above method for isolating from a cDNA expression library a G-protein associated receptor which deactivates the inward rectifier, G-protein activated, mammalian potassium KGA channel.

The invention provides a G-protein associated receptor capable of deactivating the inward rectifier, G-protein activated, mammalian potassium KGA channel isolated by the above method for isolating from a cDNA expression library a G-protein associated receptor which deactivates the inward rectifier, G-protein activated, mammalian potassium KGA channel.

This invention provides a method for identifying an inhibitory G-protein associated receptor which deactivates the inward rectifier, G-protein activated, mammalian KGA potassium channel comprising: (a) introducing the nucleic acid molecule encoding an inward rectifier, G-protein

activated, mammalian, potassium KGA channel, a G-protein associated receptor known to activate the KGA channel, and nucleic acid molecules encoding an inhibitory G-protein associated receptor to a *Xenopus* oocyte under conditions
5 permitting expression of both the receptors and the channel;
(b) contacting the oocyte of step (b) with a known G-protein associated receptor activator and a known inhibitory G-protein associated receptor activator; and (c) detecting any
10 change in KGA channel conductance, a decrease in KGA channel
conductance indicating that the G-protein associated
receptor deactivates the KGA channel.

This invention provides an antibody directed against the purified inward rectifier, G-protein activated, mammalian, potassium KGA channel. In an embodiment, this antibody is
15 monoclonal antibody.

This invention will be better understood from the Experimental Details which follow. However, one skilled in the art will readily appreciate that the specific methods and results discussed are merely illustrative of the
20 invention as described more fully in the claims which follow thereafter.

EXPERIMENTAL MATERIALS AND METHODS

Preparation of RNA and oocytes. Total RNA was extracted from atria and ventricles of 19-21 day old rats of both sexes
25 using the Chomczynski-Sacchi procedure (33). Poly (A) RNA was separated on an oligo-dT cellulose column (type 3, Collaborative Biochemical Products). Ventricle poly(A) RNA was fractionated by centrifugation (18 h, 30,000 g, 4°C) on a linear 5%-25% sucrose gradient. *Xenopus laevis* oocytes
30 were prepared as described (34) and injected with either 50-120 ng/oocyte poly(A) RNA, 120-200 ng/oocyte total RNA, or 35 ng/oocyte fractionated poly(A) RNA. In most cases, 5HT1A-R RNA (5-20 ng/oocyte) was co-injected with atrial or ventricle RNA. Final volume of the injected RNA solution

was 50 nl. The oocytes were incubated for 3-7 days in the NDE solution (ND96 (see below) containing 1.8 mM CaCl_2 and supplemented with 2.5 mM Na-pyruvate and 50 $\mu\text{g/ml}$ gentamicin). Occasionally, either 2.5-5% heat-inactivated horse serum or 0.5 mM theophylline were added to the NDE solution. Incubation of oocytes in pertussis toxin (PTX; List Biochemicals) was done in NDE solution without the addition of pyruvate, serum or theophylline. cDNAs of 5HT1A receptor (see 23) and $G_{i2}\alpha$ (a gift from M. I. Simon, Caltech) in pBluescript were linearized, and RNA was synthesized *in vitro* as described (34).

Electrophysiological recordings were performed using the two electrode voltage clamp method with the Dagan 8500 amplifier (Dagan Instruments, Minneapolis) as described (35). The oocytes were usually kept in the ND96 solution: 96 mM NaCl/2 mM KCl/1 mM MgCl_2 /1 mM CaCl_2 /5 mM Hepes, pH=7.5. Most measurements were done in the high K^+ solution (hK): 96 mM KCl/2 mM NaCl/1 mM MgCl_2 /1 mM CaCl_2 /5 mM Hepes, pH=7.5. Solutions containing intermediate concentrations of K^+ were made by substituting K^+ for Na^+ . Solution exchange and drug application were done by superfusing the cell placed in a 0.5 ml chamber. GDP- β -S(trilithium salt; Sigma) was injected by pressure (35). Stimulation, data acquisition, and analysis were performed using pCLAMP software (Axon Instruments, Foster City, CA).

EXPERIMENTAL RESULTS

To express the KG channel, the oocytes were injected with atrial total or poly(A) RNA. In order to avoid the possibility that a low level of expression of the muscarinic receptor will make undetectable even a well-expressed KG channel, atrial RNA was usually supplemented with mRNA coding for the serotonin-5HT1A receptor (5HT1A-R); oocytes injected with this RNA mixture will be termed RNA-injected oocytes throughout the paper. When expressed in atrial myocytes, the 5HT1A-R efficiently coupled to the KG channel

normally existing in these cells (23), and it was expected to do so in the oocytes.

Four to 5 days after RNA injection addition of 10 μ M ACh or 1-2 μ M 5HT to the ND96 bath solution did not cause any significant change in membrane current. Therefore, the effects of ACh and 5HT were tested in a high potassium (hK) solution with 96 mM K^+ and 2 mM Na^+ . In this solution, the K^+ equilibrium potential (E_K) is close to 0 mV, and this enables inward K^+ current flow through inwardly rectifying K channels at negative holding potentials (-80 mV was routinely used in this study).

Changing ND 96 to the hK solution was accompanied by the development of an inward current that reached a steady level within 0.5-1 min (I_{hK} ; Fig 1A). I_{hK} was also observed in native (not injected with any RNA) oocytes, or in oocytes injected with 5HT1A-R RNA alone, but it was always larger in RNA-injected oocytes ($P < 0.001$, two-tailed t-test; Table 1).

Table 1

Inward currents evoked by high K^+ and by 5HT. The entries are inward currents in nA shown as mean $\pm$ SEM (n), measured at -80mV in the hK solution. 5HT concentration ranged in 5 different experiments from 100 nM to 2 μ M.

Injected RNA	I_{hK}	I_{5HT}
None (native oocytes)	72 $\pm$ 6 (34)	0 (18)
5HT1A-R	54 $\pm$ 4 (11)	0 (12)
Atrial + 5HT1A-R	123 $\pm$ 8 (55)	290 $\pm$ 43 (55)

- 10 In RNA-injected oocytes, application of 5HT or ACh in hK solution induced an inward current (I_{5HT}) that subsided upon washout of the transmitter (Fig. 1A, B). The response to ACh was usually smaller than to 5HT when measured in the oocytes of the same frog (Fig. 1B). Thus, in oocytes of one
- 15 frog I_{5HT} was 1102 $\pm$ 84 nA (n=6), whereas the ACh response was 382 $\pm$ 45 nA (n=6). I_{5HT} tended to decrease on repeated applications of 5HT, and this could be overcome by increasing the intervals between applications to 10 min or more, suggesting the presence of a desensitization process.
- 20 I_{5HT} and an increased (in comparison with native oocytes) I_{hK} were also observed in oocytes injected with ventricle poly(A) RNA + 5HT1A-R RNA, but the I_{5HT} was about 20 times smaller than with atrial poly(A) RNA (not shown). 5HT had no effect in oocytes injected with atrial RNA without the
- 25 5HT1A-R RNA (n=4) or with 5HT1A-R RNA alone, or in native oocytes (Table 1).

The 5HT dose-response curve showed saturation at about 100 nM and a half-maximal response at about 15 nM (Fig. 1C), which is characteristic of the 5HT1 receptor class (36). A

30 similar current was evoked by a selective 5HT1A agonist, 8-OH DPAT (8-OH-2-(D1-n-(propylamino))-tetralin; data not shown).

The current-voltage (I-V) characteristic of the oocyte membrane was studied by applying voltage steps from a holding potential of -80 mV. In normal ND96, in the range -140 - -20 mV, only voltage- and time-independent "leak" currents were observed (Fig. 2a), and the I-V curve was linear (Fig. 2B). Above -20 mV, a slowly developing outward current was observed (Fig. 2A, a-c); this is known to be due to opening of a Cl^- channel activated by Ca^{2+} entry through voltage-dependent Ca^{2+} channels (37). The Ca^{2+} -activated Cl^- current was also seen in the hK solution; in addition, the total membrane current evoked by steps to -120 and up to -20 mV was larger than in ND96 (Fig. 2Ab; 2B), whereas above 0 mV there was little or no change. This suggested that most or all of I_{hK} elicited at -80 mV by the exchange of ND96 to hK solution was due to a K^+ current flowing through a constitutively active inward rectifier K^+ channel(s). This current showed some time-dependent inactivation at -140 mV (Fig. 2Ab) and at more negative potentials (not shown); this inactivation phenomenon was not studied further. In the presence of 5HT, the membrane currents between -140 and -20 mV were further increased (Fig. 2Ac). Net 5HT-evoked currents, obtained by digital subtraction of total membrane currents in the absence of 5HT from currents in its presence (Fig. 2Ad), showed clear inward rectification; the 5HT-activated channels conducted little or no current above E_{K} at different external K^+ concentrations, $[\text{K}_{\text{out}}]$ (Fig. 2C). The extrapolated reversal potential of I_{5HT} showed an almost perfect selectivity of the 5HT-activated channel to K^+ , changing by about 58 mV per 10-fold change in $[\text{K}_{\text{out}}]$ (Fig. 2D). The reversal potential of the total membrane current in the absence of 5HT also depended on $[\text{K}_{\text{out}}]$ (Fig. 2B) but changed only by 24 mV per tenfold change in $[\text{K}_{\text{out}}]$ (Fig. 2D). This does not necessarily imply poor ion selectivity of the constitutively active inward rectifier, but may reflect the relatively high contribution of Cl^- and Na^+ to the resting membrane conductance (38).

Block by external Ba^{2+} is one of the characteristic features of inward rectifiers (24). In normal ND96 solution, Ba^{2+} (5 μM -3 mM) did not cause any significant changes in resting current or conductance in native or RNA-injected oocytes at the holding potential of -80mV. In the hK solution, Ba^{2+} inhibited both I_{hK} and I_{5HT} (Fig. 3), and this was accompanied by a decrease in membrane conductance (not shown). 300 μM , Ba^{2+} blocked about 20% of I_{hK} but almost completely abolished I_{5HT} (Fig. 3B). The IC_{50} (half-inhibition concentration) for Ba^{2+} block of I_{5HT} was about 15 μM , whereas IC_{50} for I_{hK} block was above 3 mM (Fig. 3D). It is noteworthy that, although the sensitivity of I_{hK} to Ba^{2+} block was similar in native and RNA-injected oocytes, the latter did appear to have a small component of I_{hK} inhibited by low doses of Ba^{2+} (Fig. 3D). This raises the possibility that the atrial I_{hK} is more sensitive to Ba^{2+} block than the oocyte's I_{hK} , or that a fraction of the highly Ba^{2+} -sensitive channels underlying I_{5HT} could be active in the absence of agonist. Note also that there was an inward current "tail" observed when Ba^{2+} and 5HT was washed out simultaneously (Fig. 3B), presumably because the rate-limiting step in deactivation of the channel proceeds more slowly than unblock from Ba^{2+} .

To estimate the size of RNA encoding the expressed inward rectifiers, ventricle poly(A) RNA (available in large amounts) was fractionated on a sucrose gradient. The size distribution of the fractions was measured by RNA gel blots probed with [^{32}P]-labeled poly(T) (39). The RNA encoding I_{5HT} was found mainly in two size fractions covering the range between 2.5 and 5.5 kb. The peak expression of ventricle I_{hK} was in lower size fractions, in the 1.5-3 kb range (data not shown).

In atrium, the muscarinic receptor is coupled to the KG channel via a PTX-sensitive G-protein (8). Surprisingly, in RNA-injected oocytes, I_{5HT} was not affected by treatment with PTX; neither was I_{hK} (Fig. 4A). To test whether the 5HT1A

receptor couples to the K^+ channel via a G-protein, the oocytes were injected with 400-800 pmole/oocyte of the non-hydrolysable analog of GDP, GDP- β -S, that is known to inhibit the activity of PTX-sensitive as well as of PTX-insensitive G-proteins (40). In 4 cells, GDP- β -S injection had no effect on I_{hK} ($115 \pm 8\%$ of control) but strongly inhibited I_{5HT} , to $4 \pm 1\%$ of control (Fig. 4B). Thus, it appears that the coupling between the 5HT1A receptor and the KG channel occurs via an oocyte's endogenous PTX-insensitive G-protein.

We examined whether an overexpressed PTX-sensitive α subunit of a G-protein, e.g. $G_{i2}\alpha$, could compete with the "native" PTX-insensitive α subunit for the expressed 5HT1A receptor, thus restoring the PTX sensitivity of the KG channel activation. As shown in Fig. 4A, in oocytes injected with atrial RNA plus cRNAs encoding 5HT1A-R and $G_{i2}\alpha$, PTX inhibited I_{5HT} by about 50% ($P < 0.01$, two-tailed t-test), whereas I_{hK} was unaffected.

EXPERIMENTAL DISCUSSION

The present results demonstrate for the first time that the atrial inward rectifier K^+ (KG) channel, which in the native tissue is activated by ACh via a PTX-sensitive G-protein, is expressed in oocytes injected with atrial RNA. Current through the channel can be activated by acetylcholine (ACh) or, if RNA encoding a neuronal 5HT1A receptor is co-injected with atrial RNA, by serotonin (5HT). Activation of the channel probably occurs via a muscarinic ACh receptor synthesized following atrial RNA injection, rather than via the oocyte's endogenous muscarinic receptor. The latter couples to phospholipase C, and its activation induces very characteristic large transient Cl^- current responses caused by Ca^{2+} release from intracellular stores (41). Fortunately, the majority of oocyte batches lose this response after defolliculation (42), and this response was not observed in the present study. Because the ACh-evoked

currents were small in most cases, we concentrated on the study of the 5HT response; the latter was undoubtedly mediated by the introduced 5HT1A receptor, as 5HT was ineffective in oocytes not injected with 5HT1A-RNA, and the response displayed the expected pharmacological properties.

The evidence presented here indicates that, in oocytes injected with atrial and 5HT1A-R RNAs, activation of the 5HT1A receptor leads to opening of a K^+ channel that bears distinctive features of an anomalous rectifier, similar to those of the atrial KG: i) it conducts inward but not outward K^+ current; ii) it is blocked by low concentrations of Ba^{2+} , iii) the conductance of the channel does not depend solely on voltage but on $(E-E_K)$. The expression of this channel must truly be directed by atrial RNA, because: i) no hormone or transmitter-activated current of this kind is observed in native oocytes; ii) expression of 5HT1A receptor alone does not cause the appearance of such a response. Based on ventricle RNA fractionation data, the RNA encoding the 5HT-activated channel is in a broad size range between 2.5 and 5.5 kb. This is similar or somewhat smaller than the reported 4-5 kb mRNA size of some constitutively active inward rectifiers expressed in *Xenopus* oocytes (43, 44), as well as of the cloned IRK1 (5.5 kb; ref. 31) and ROMK1 (4 kb; ref. 30) channels. The properties of I_{5HT} directed by ventricle and atrial RNA are very similar, and it is reasonable to assume that they are encoded by the same RNA species.

Opening of the inward rectifier by 5HT is mediated by activation of a G-protein, as expected for the KG channel, because i) 5HT1A receptor belongs to the family of 7-helix receptors all of which act via G-proteins (40); ii) I_{5HT} was inhibited by intracellular injection of GDP- β -S. However, the G-protein participating in this pathway was PTX-insensitive, possibly an endogenous oocyte G-protein. It is not clear why in the oocyte the channel activation pathway involves a PTX-insensitive G-protein. The atrial KG channel

normally couples to G_i (9), and there are at least two subspecies of G_i in the oocyte (45); also, some G_i may be expressed from atrial RNA. Also, in the hippocampus, the 5HT_{1A} receptor opens a K^+ channel by activating a PTX-sensitive G-protein (21). One possibility is that a vast excess of this undefined PTX-insensitive G-protein overrides the others in competition for coupling to the 5HT_{1A} receptor. Whatever the reason for this unexpected coupling, our results show that the PTX sensitivity of the KG channel activation can be partially restored by overexpression of the α subunit of G_i . Since the actual identify of the α subunit does not seem to be important for activation of the expressed KG channel, these results imply that the $\beta\gamma$ subunit complex doublet may be the activator of the channel in this case (cf. 10, 11).

Atrial and ventricle RNAs also induce an enhanced activity of an additional inward rectifier, that is active in the absence of any specific stimulation (referred to as I_{hK} in this paper). I_{hK} in atrial RNA-injected oocytes is about twice as large as in native oocytes or oocytes injected with 5HT_{1A}-R RNA alone. This current does not appear to represent the "basal" activity of the same channel activated by 5HT or ACh because it has a much lower sensitivity to Ba^{2+} block. Moreover, the fractionation data indicates that the RNA directing the expression of I_{hK} is smaller than that encoding the KG channel. However, it is not clear whether this atrial (or ventricle) RNA encodes the channel itself or a factor that enhances the expression or the activity of a native channel. Further studies, such as expression cloning, will help to identify the messages encoding the two inward rectifiers whose expression is reported here.

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SEQUENCE LISTING

(1) GENERAL INFORMATION:

- (i) APPLICANTS: Lester, Henry A., et al.
- (ii) TITLE OF INVENTION: DNA ENCODING INWARD RECTIFIER, G-PROTEIN ACTIVATED, MAMMALIAN, POTASSIUM KGA CHANNEL AND USES THEREOF
- (iii) NUMBER OF SEQUENCES: 2
- (iv) CORRESPONDENCE ADDRESS:
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- (v) COMPUTER READABLE FORM:
 - (A) MEDIUM TYPE: Floppy disk
 - (B) COMPUTER: IBM PC compatible
 - (C) OPERATING SYSTEM: PC-DOS/MS-DOS
 - (D) SOFTWARE: PatentIn Release #1.0, Version #1.25
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- (viii) ATTORNEY/AGENT INFORMATION:
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(2) INFORMATION FOR SEQ ID NO:1:

- (i) SEQUENCE CHARACTERISTICS:
 - (A) LENGTH: 2076 base pairs
 - (B) TYPE: nucleic acid
 - (C) STRANDEDNESS: single
 - (D) TOPOLOGY: linear

(ii) MOLECULE TYPE: cDNA

- (ix) FEATURE:
 - (A) NAME/KEY: CDS
 - (B) LOCATION: 32..1534

(xi) SEQUENCE DESCRIPTION: SEQ ID NO:1:

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TTT GGG GAC GAT TAC CAG GTA GTG ACC ACT TCG TCC AGC GGT TCG GGC	100
Phe Gly Asp Asp Tyr Gln Val Val Thr Thr Ser Ser Ser Gly Ser Gly	
10 15 20	

TTG	CAG	CCC	CAG	GGG	CCA	GGA	CAG	GGC	CCA	CAG	CAG	CAG	CTT	GTA	CCC	148
Leu	Gln	Pro	Gln	Gly	Pro	Gly	Gln	Gly	Pro	Gln	Gln	Gln	Leu	Val	Pro	
	25					30						35				
AAG	AAG	AAA	CGG	CAG	CGG	TTC	GTG	GAC	AAG	AAC	GGT	CGG	TGC	AAT	GTG	196
Lys	Lys	Lys	Arg	Gln	Arg	Phe	Val	Asp	Lys	Asn	Gly	Arg	Cys	Asn	Val	
	40				45					50					55	
CAG	CAC	GGC	AAC	CTG	GGC	AGC	GAG	ACC	AGT	CGC	TAC	CTT	TCC	GAC	CTC	244
Gln	His	Gly	Asn	Leu	Gly	Ser	Glu	Thr	Ser	Arg	Tyr	Leu	Ser	Asp	Leu	
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TTC	ACT	ACC	CTG	GTG	GAT	CTC	AAG	TGG	CGT	TGG	AAC	CTC	TTT	ATC	TTC	292
Phe	Thr	Thr	Leu	Val	Asp	Leu	Lys	Trp	Arg	Trp	Asn	Leu	Phe	Ile	Phe	
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ATC	CTC	ACC	TAC	ACC	GTG	GCC	TGG	CTC	TTC	ATG	GCG	TCC	ATG	TGG	TGG	340
Ile	Leu	Thr	Tyr	Thr	Val	Ala	Trp	Leu	Phe	Met	Ala	Ser	Met	Trp	Trp	
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GTG	ATC	GCT	TAT	ACC	CGG	GGC	GAC	CTG	AAC	AAA	GCC	CAT	GTC	GGC	AAC	388
Val	Ile	Ala	Tyr	Thr	Arg	Gly	Asp	Leu	Asn	Lys	Ala	His	Val	Gly	Asn	
	105					110					115					
TAC	ACT	CCC	TGT	GTG	GCC	AAT	GTC	TAT	AAC	TTC	CCC	TCT	GCC	TTC	CTT	436
Tyr	Thr	Pro	Cys	Val	Ala	Asn	Val	Tyr	Asn	Phe	Pro	Ser	Ala	Phe	Leu	
	120				125					130					135	
TTC	TTC	ATC	GAG	ACC	GAG	GCC	ACC	ATC	GGC	TAT	GGC	TAC	CGC	TAC	ATC	484
Phe	Phe	Ile	Glu	Thr	Glu	Ala	Thr	Ile	Gly	Tyr	Gly	Tyr	Arg	Tyr	Ile	
			140						145					150		
ACC	GAC	AAG	TGC	CCC	GAG	GGC	ATC	ATC	CTT	TTC	CTT	TTC	CAG	TCC	ATC	532
Thr	Asp	Lys	Cys	Pro	Glu	Gly	Ile	Ile	Leu	Phe	Leu	Phe	Gln	Ser	Ile	
			155				160						165			
CTT	GGC	TCC	ATC	GTG	GAC	GCT	TTC	CTC	ATC	GGC	TGC	ATG	TTC	ATC	AAG	580
Leu	Gly	Ser	Ile	Val	Asp	Ala	Phe	Leu	Ile	Gly	Cys	Met	Phe	Ile	Lys	
		170					175					180				
ATG	TCC	CAG	CCC	AAA	AAG	CGC	GCC	GAG	ACC	CTC	ATG	TTT	AGC	GAG	CAT	628
Met	Ser	Gln	Pro	Lys	Lys	Arg	Ala	Glu	Thr	Leu	Met	Phe	Ser	Glu	His	
	185					190					195					
GCG	GTT	ATT	TCC	ATG	AGG	GAC	GGA	AAA	CTC	ACT	CTC	ATG	TTC	CGG	GTG	676
Ala	Val	Ile	Ser	Met	Arg	Asp	Gly	Lys	Leu	Thr	Leu	Met	Phe	Arg	Val	
	200				205					210					215	
GGC	AAC	CTG	CGC	AAC	AGC	CAC	ATG	GTC	TCC	GCG	CAG	ATC	CGC	TGC	AAG	724
Gly	Asn	Leu	Arg	Asn	Ser	His	Met	Val	Ser	Ala	Gln	Ile	Arg	Cys	Lys	
			220						225					230		
CTG	CTC	AAA	TCT	CGG	CAG	ACA	CCT	GAG	GGT	GAG	TTT	CTA	CCC	CTT	GAC	772
Leu	Leu	Lys	Ser	Arg	Gln	Thr	Pro	Glu	Gly	Glu	Phe	Leu	Pro	Leu	Asp	
			235					240					245			
CAA	CTT	GAA	CTG	GAT	GTA	GGT	TTT	AGT	ACA	GGG	GCA	GAT	CAA	CTT	TTT	820
Gln	Leu	Glu	Leu	Asp	Val	Gly	Phe	Ser	Thr	Gly	Ala	Asp	Gln	Leu	Phe	
		250					255					260				
CTT	GTG	TCC	CCT	CTC	ACC	ATT	TGC	CAC	GTG	ATC	GAT	GCC	AAA	AGC	CCC	868
Leu	Val	Ser	Pro	Leu	Thr	Ile	Cys	His	Val	Ile	Asp	Ala	Lys	Ser	Pro	
	265					270					275					
TTT	TAT	GAC	CTA	TCC	CAG	CGA	AGC	ATG	CAA	ACT	GAA	CAG	TTC	GAG	GTG	916
Phe	Tyr	Asp	Leu	Ser	Gln	Arg	Ser	Met	Gln	Thr	Glu	Gln	Phe	Glu	Val	
	280				285					290					295	

GTC Val	GTC Val	ATC Ile	CTG Leu	GAA Glu 300	GGC Gly	ATC Ile	GTG Val	GAA Glu	ACC Thr 305	ACA Thr	GGG Gly	ATG Met	ACT Thr	TGT Cys 310	CAA Gln	964
GCT Ala	CGA Arg	ACA Thr	TCA Ser 315	TAC Tyr	ACC Thr	GAA Glu	GAT Asp	GAA Glu 320	GTT Val	CTT Leu	TGG Trp	GGT Gly	CAT His 325	CGT Arg	TTT Phe	1012
TTC Phe	CCT Pro	GTA Val 330	ATT Ile	TCT Ser	TTA Leu	GAA Glu	GAA Glu 335	GGA Gly	TTC Phe	TTT Phe	AAA Lys 340	GTC Val	GAT Asp	TAC Tyr	TCC Ser	1060
CAG Gln 345	TTC Phe	CAT His	GCA Ala	ACC Thr	TTT Phe	GAA Glu 350	GTC Val	CCC Pro	ACC Thr	CCT Pro	CCG Pro 355	TAC Tyr	AGT Ser	GTG Val	AAA Lys	1108
GAG Glu 360	CAG Gln	GAA Glu	GAA Glu	ATG Met	CTT Leu 365	CTC Leu	ATG Met	TCT Ser	TCC Ser	CCT Pro 370	TTA Leu	ATA Ile	GCA Ala	CCA Pro	GCC Ala 375	1156
ATA Ile	ACC Thr	AAC Asn	AGC Ser 380	AAA Lys	GAA Glu	AGA Arg	CAC His	AAT Asn 385	TCT Ser	GTG Val	GAG Glu	TGC Cys	TTA Leu	GAT Asp 390	GGA Gly	1204
CTA Leu	GAT Asp	GAC Asp	ATT Ile 395	AGC Ser	ACA Thr	AAA Lys	CTT Leu	CCA Pro 400	TCG Ser	AAG Lys	CTG Leu	CAG Gln	AAA Lys 405	ATT Ile	ACG Thr	1252
GGG Gly	AGA Arg	GAA Glu 410	GAC Asp	TTT Phe	CCC Pro	AAA Lys	AAA Lys 415	CTC Leu	CTG Leu	AGG Arg	ATG Met	AGT Ser 420	TCT Ser	ACA Thr	ACT Thr	1300
TCA Ser	GAA Glu 425	AAA Lys	GCC Ala	TAT Tyr	AGT Ser	TTG Leu 430	GGT Gly	GAT Asp	TTG Leu	CCC Pro	ATG Met 435	AAA Lys	CTC Leu	CAA Gln	CGA Arg	1348
ATA Ile 440	AGT Ser	TCG Ser	GTT Val	CCT Pro	GGC Gly 445	AAC Asn	TCT Ser	GAA Glu	GAA Glu	AAA Lys 450	CTG Leu	GTA Val	TCT Ser	AAA Lys 455	ACC Thr	1396
ACC Thr	AAG Lys	ATG Met	TTA Leu 460	TCA Ser	GAT Asp	CCC Pro	ATG Met	AGC Ser	CAG Gln 465	TCT Ser	GTG Val	GCC Ala	GAT Asp	TTG Leu 470	CCA Pro	1444
CCG Pro	AAG Lys	CTT Leu	CAA Gln 475	AAG Lys	ATG Met	GCT Ala	GGA Gly	GGA Gly 480	CCT Pro	ACC Thr	AGG Arg	ATG Met	GAA Glu 485	GGG Gly	AAT Asn	1492
CTT Leu	CCA Pro	GCC Ala 490	AAA Lys	CTA Leu	AGA Arg	AAA Lys	ATG Met 495	AAC Asn	TCT Ser	GAC Asp	CGC Arg	TTC Phe 500	ACA Thr			1534
TAGCAAAACA CCCCATTAGG CATTATTTCA TGTTTTGATT TAGTTTTAGT CCAATATTTG																1594
GCTGATAAGA TAATCCTCCC CGGGAAATCT GAGAGGTCTA TCCCAGTCTG GCAAATTCAT																1654
CAGAGGACTC TTCATTGAAG TGTTGTTACT GTGTTGAACA TGAGTTACAA AGGGAGGACA																1714
TCATAAGAAA GCTAATAGTT GGCATGTATT ATCACATCAA GCATGCAATA ATGTGCAAAT																1774
TTTGCATTTA GTTTTCTGGC ATGATTTATA TATGGCATAT TTATATTGAA TATTCTGGAA																1834
AAATATATAA ATATATATTT GAAGTGGAGA TATTCTCCCC ATAATTTCTA ATATATGTAT																1894
TAAGCCAAAC ATGAGTGGAT AGCTTTCAGG GCACTAAAAT AATATACATG CATACATACA																1954
TACATGCATA TGCACAGACA CATAACACA CATACTCATA TATATAAAAC ATACCCATAC																2014

AAACATATAT ATCTAATAAA AATTGTGATG TTTTGTTCAG AAAAAAAAAA AAAAAACTCG 2074
AG 2076

(2) INFORMATION FOR SEQ ID NO:2:

(i) SEQUENCE CHARACTERISTICS:

- (A) LENGTH: 501 amino acids
- (B) TYPE: amino acid
- (D) TOPOLOGY: linear

(ii) MOLECULE TYPE: protein

(xi) SEQUENCE DESCRIPTION: SEQ ID NO:2:

Met	Ser	Ala	Leu	Arg	Arg	Lys	Phe	Gly	Asp	Asp	Tyr	Gln	Val	Val	Thr	1	5	10	15
Thr	Ser	Ser	Ser	Gly	Ser	Gly	Leu	Gln	Pro	Gln	Gly	Pro	Gly	Gln	Gly	20	25	30	
Pro	Gln	Gln	Gln	Leu	Val	Pro	Lys	Lys	Arg	Gln	Arg	Phe	Val	Asp	35	40	45		
Lys	Asn	Gly	Arg	Cys	Asn	Val	Gln	His	Gly	Asn	Leu	Gly	Ser	Glu	Thr	50	55	60	
Ser	Arg	Tyr	Leu	Ser	Asp	Leu	Phe	Thr	Thr	Leu	Val	Asp	Leu	Lys	Trp	65	70	75	80
Arg	Trp	Asn	Leu	Phe	Ile	Phe	Ile	Leu	Thr	Tyr	Thr	Val	Ala	Trp	Leu	85	90	95	
Phe	Met	Ala	Ser	Met	Trp	Trp	Val	Ile	Ala	Tyr	Thr	Arg	Gly	Asp	Leu	100	105	110	
Asn	Lys	Ala	His	Val	Gly	Asn	Tyr	Thr	Pro	Cys	Val	Ala	Asn	Val	Tyr	115	120	125	
Asn	Phe	Pro	Ser	Ala	Phe	Leu	Phe	Phe	Ile	Glu	Thr	Glu	Ala	Thr	Ile	130	135	140	
Gly	Tyr	Gly	Tyr	Arg	Tyr	Ile	Thr	Asp	Lys	Cys	Pro	Glu	Gly	Ile	Ile	145	150	155	160
Leu	Phe	Leu	Phe	Gln	Ser	Ile	Leu	Gly	Ser	Ile	Val	Asp	Ala	Phe	Leu	165	170	175	
Ile	Gly	Cys	Met	Phe	Ile	Lys	Met	Ser	Gln	Pro	Lys	Lys	Arg	Ala	Glu	180	185	190	
Thr	Leu	Met	Phe	Ser	Glu	His	Ala	Val	Ile	Ser	Met	Arg	Asp	Gly	Lys	195	200	205	
Leu	Thr	Leu	Met	Phe	Arg	Val	Gly	Asn	Leu	Arg	Asn	Ser	His	Met	Val	210	215	220	
Ser	Ala	Gln	Ile	Arg	Cys	Lys	Leu	Leu	Lys	Ser	Arg	Gln	Thr	Pro	Glu	225	230	235	240
Gly	Glu	Phe	Leu	Pro	Leu	Asp	Gln	Leu	Glu	Leu	Asp	Val	Gly	Phe	Ser	245	250	255	
Thr	Gly	Ala	Asp	Gln	Leu	Phe	Leu	Val	Ser	Pro	Leu	Thr	Ile	Cys	His	260	265	270	

Val Ile Asp Ala Lys Ser Pro Phe Tyr Asp Leu Ser Gln Arg Ser Met
 275 280 285
 Gln Thr Glu Gln Phe Glu Val Val Val Ile Leu Glu Gly Ile Val Glu
 290 295 300
 Thr Thr Gly Met Thr Cys Gln Ala Arg Thr Ser Tyr Thr Glu Asp Glu
 305 310 315 320
 Val Leu Trp Gly His Arg Phe Phe Pro Val Ile Ser Leu Glu Glu Gly
 325 330 335
 Phe Phe Lys Val Asp Tyr Ser Gln Phe His Ala Thr Phe Glu Val Pro
 340 345 350
 Thr Pro Pro Tyr Ser Val Lys Glu Gln Glu Glu Met Leu Leu Met Ser
 355 360 365
 Ser Pro Leu Ile Ala Pro Ala Ile Thr Asn Ser Lys Glu Arg His Asn
 370 375 380
 Ser Val Glu Cys Leu Asp Gly Leu Asp Asp Ile Ser Thr Lys Leu Pro
 385 390 395 400
 Ser Lys Leu Gln Lys Ile Thr Gly Arg Glu Asp Phe Pro Lys Lys Leu
 405 410 415
 Leu Arg Met Ser Ser Thr Thr Ser Glu Lys Ala Tyr Ser Leu Gly Asp
 420 425 430
 Leu Pro Met Lys Leu Gln Arg Ile Ser Ser Val Pro Gly Asn Ser Glu
 435 440 445
 Glu Lys Leu Val Ser Lys Thr Thr Lys Met Leu Ser Asp Pro Met Ser
 450 455 460
 Gln Ser Val Ala Asp Leu Pro Pro Lys Leu Gln Lys Met Ala Gly Gly
 465 470 475 480
 Pro Thr Arg Met Glu Gly Asn Leu Pro Ala Lys Leu Arg Lys Met Asn
 485 490 495
 Ser Asp Arg Phe Thr
 500

WHAT IS CLAIMED IS:

1. An isolated nucleic acid molecule encoding an inward rectifier, G-protein activated, mammalian, potassium KGA channel.
- 5 2. An isolated RNA molecule of claim 1.
3. An isolated DNA molecule of claim 1.
4. An isolated cDNA molecule of claim 3.
5. A plasmid comprising the molecule of claim 1.
6. The plasmid of claim 5, designated pBSIIKS(-)KGA (ATCC
10 Accession No. 75469).
7. A nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with the nucleic acid molecule of claim 1.
8. An isolated nucleic acid molecule of claim 1,
15 operatively linked to a promoter of RNA transcription.
9. A vector comprising the nucleic acid molecule of claim 8.
10. A host vector system for the production of a polypeptide having the biological activity of a KGA channel
20 which comprises the vector of claim 9 in a suitable host.
11. A host vector system of claim 10, wherein the suitable host is a bacterial cell, an insect cell, a mammalian cell, or a *Xenopus* oocyte.
12. A method for producing a polypeptide having the
25 biological activity of a KGA channel which comprises culturing the host vector system of claim 10 under

conditions permitting production of the polypeptide and recovering the polypeptide so produced.

13. A method for isolating from a sample a nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel which comprises:
- (a) isolating nucleic acids from the sample;
 - (b) contacting the isolated nucleic acids with the molecule of claim 7, under conditions permitting formation of a complex between the nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel and the molecule of claim 7;
 - (c) isolating the complex so formed; and
 - (d) separating the nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel from the complex, thereby isolating the nucleic acid molecule encoding an inward rectifier, G-protein activated, potassium channel.

14. A method for isolating DNA encoding an inward rectifier, G-protein activated, potassium channel or a fragment thereof in a sample which comprises:
- (a) isolating DNA from the sample;
 - (b) denaturing the isolated DNA;
 - (c) reannealing the denatured DNA in the presence of two unique single stranded nucleic acid molecules of claim 7 that are complementary to nucleotide sequences on opposite strands of the DNA molecule encoding an inward rectifier, G-protein activated, mammalian, potassium KGA channel;
 - (d) polymerizing the reannealed nucleic acids with DNA polymerase under conditions that allow DNA polymerization;
 - (e) denaturing the polymerized DNA of step (d);
 - (f) repeating steps (c) through (e) for 10 or more cycles; and
 - (g) isolating the polymerized DNA obtained from step (f), thereby isolating DNA encoding an inward rectifier, G-protein activated, potassium channel or a fragment thereof.

15. A method for isolating DNA encoding an inward rectifier, G-protein activated, potassium channel or a fragment thereof in a sample which comprises:
- (a) isolating DNA from the sample;
 - 5 (b) denaturing the isolated DNA;
 - (c) reannealing the denatured DNA in the presence of a unique single stranded nucleic acid molecule of claim 7 and a nucleic acid molecule encoding a known genomic repeat sequence;
 - 10 (d) polymerizing the reannealed nucleic acids with DNA polymerase under conditions that allow DNA polymerization;
 - (e) denaturing the polymerized DNA of step (d); and
 - (f) repeating steps (c) through (e) for 10 or more cycles; and
 - 15 (g) isolating the polymerized DNA from step (f), thereby isolating DNA encoding an inward rectifier, G-protein activated, potassium channel or a fragment thereof.
- 20 16. A method of claim 13, wherein the molecule of claim 7 is labelled with a detectable marker.
17. A nucleic acid molecule isolated by the method of claim 13.
18. A purified inward rectifier, G-protein activated,
25 mammalian, potassium KGA channel.
19. A purified channel of claim 18, having substantially the same amino acid sequence as the amino acid sequence shown in Figure 5.
20. A protein encoded by the isolated nucleic acid molecule
30 of claim 1.
21. A method for determining whether an agent activates a KGA channel which comprises:

- (a) contacting the host vector system of claim 10 with the agent under conditions permitting KGA channel conductance to be affected by known ion channel agonists or intracellular second messenger agonists; and
- 5 (b) detecting any change in KGA channel conductance, an increase in KGA channel conductance indicating that the agent activates the KGA channel.

22. An agent identified by the method of claim 21.

23. A pharmaceutical composition comprising an amount of
10 the agent of claim 22, effective to increase KGA conductance and a pharmaceutical acceptable carrier.

24. A method for determining whether an agent deactivates a KGA channel which comprises:

- (a) contacting the host vector system of claim 10 with
15 the agent under conditions permitting KGA channel conductance to be affected by known ion channel antagonists or intracellular second messenger system agonist; and
- (b) detecting any change in KGA channel conductance, a decrease in KGA channel conductance indicating that the
20 agent deactivates the KGA channel.

25. An agent identified by the method of claim 24.

26. A pharmaceutical composition comprising an amount of the agent of claim 25, effective to decrease KGA channel conductance and a pharmaceutical acceptable carrier.

25 27. A method for identifying in a nucleic acid sample a nucleic acid molecule encoding a G-protein associated receptor which activates the inward rectifier, G-protein activated, mammalian, KGA potassium channel which comprises:

- (a) introducing nucleic acid molecules of claim 1 and
30 the nucleic acid sample to a *Xenopus* oocyte under conditions permitting expression of both the receptor and the channel;

(b) contacting the oocyte of step (a) with a panel of known G-protein associated receptor activators; and

(c) detecting any change in KGA channel conductance, an increase in KGA channel conductance indicating the
5 identification of a nucleic acid molecule encoding a G-protein associated receptor which activates the inward rectifier, G-protein activated, mammalian, KGA potassium channel.

28. A method for isolating from a cDNA expression library
10 a cDNA clone encoding a G-protein associated receptor which activates the inward rectifier, G-protein activated, mammalian potassium KGA channel which comprises:

(a) isolating cDNA from a sample containing a number of cDNA clones from the cDNA expression library;

15 (b) transcribing the isolated cDNA to produce RNA;

(c) isolating the RNA from the transcribed cDNA;

(e) introducing the isolated RNA and together with nucleic acid molecules of claim 1 into a *Xenopus* oocyte under conditions permitting expression of the KGA channel
20 and G-protein associated receptor;

(f) contacting the oocyte of step (e) with a panel of known G-protein associated receptor activators;

(g) detecting an increase in KGA channel conductance; and

25 (h) repeating steps (a) through (g) using fewer cDNA clones from the sample until isolation of a single cDNA clone encoding a G-protein associated receptor which activates the KGA channel.

29. The cDNA clone isolated in claim 28.

30 30. The G-protein associated receptor encoded by the cDNA clone of claim 29.

31. A method for testing whether a G-protein associated receptor activates the inward rectifier, G-protein activated, mammalian, KGA potassium channel which comprises:

(a) introducing a nucleic acid molecule of claim 1 and a nucleic acid molecule encoding the G-protein associated receptor to a *Xenopus* oocyte under conditions permitting expression of both the receptor and the channel;

5 (b) contacting the oocyte of step (a) with a known G-protein associated receptor activator; and

(c) detecting any change in KGA channel conductance, an increase in KGA channel conductance indicating that the G-protein associated receptor activates the KGA channel.

10 32. A method for identifying in a nucleic acid sample a nucleic acid molecule encoding G-protein associated receptor capable of deactivating the inward rectifier, G-protein activated, mammalian KGA potassium channel comprising:

(a) introducing a nucleic acid molecule of claim 1, a
15 nucleic acid molecule encoding a G-protein associated receptor known to activate the KGA channel, and the nucleic acid sample to a *Xenopus* oocyte under conditions permitting expression of the G-protein associated receptor known to activate the KGA channel, the KGA channel and a known G-
20 protein associated receptor;

(b) contacting the oocyte of step (a) with a known G-protein associated receptor activator and a panel of known inhibitory G-protein associated receptor activators; and

(c) detecting any change in KGA channel conductance,
25 a decrease in KGA channel conductance indicating the identification of a nucleic acid molecule encoding an inhibitory G-protein associated receptor capable of deactivating the KGA channel in the sample.

33. A method for isolating from a cDNA expression library
30 a cDNA clone encoding a G-protein associated receptor which deactivates the inward rectifier, G-protein activated, mammalian potassium KGA channel which comprises:

(a) isolating cDNA from a sample containing a number of cDNA clones from the cDNA expression library;

35 (b) transcribing the isolated cDNA to produce RNA;

(c) isolating the RNA from the transcribed cDNA;

- (e) introducing the isolated RNA, a nucleic acid molecule encoding a known G-protein associated receptor which activates the KGA channel, and the nucleic acid molecule of claim 1 into a *Xenopus* oocyte under conditions
5 permitting expression of the KGA channel and both receptors;
(f) contacting the oocyte of step (e) with a panel of known G-protein associated receptor activators;
(g) detecting a decrease in KGA channel conductance;
and
10 (h) repeating steps (a) through (g) using fewer cDNA clones from the sample until isolation of a single cDNA clone encoding a G-protein associated receptor which activates the KGA channel.

34. The cDNA clone encoding the G-protein associated
15 receptor of which deactivates the inward rectifier, G-protein associated, mammalian, potassium KGA channel of claim 33.

35. The G-protein associated receptor which deactivates the
inward rectifier, G-protein associated, mammalian, potassium
20 KGA channel encoded by the cDNA clone of claim 34.

36. A method for identifying a nucleic acid molecule encoding a G-protein associated receptor capable of deactivating the inward rectifier, G-protein activated, mammalian KGA potassium channel comprising:

25 (a) introducing the nucleic acid molecule of claim 1, a nucleic acid molecule encoding a G-protein associated receptor known to activate the KGA channel, and nucleic acid molecules encoding an G-protein associated receptor to a *Xenopus* oocyte under conditions permitting expression of
30 both the receptors and the channel;

(b) contacting the oocyte of step (b) with a known activator for the G-protein associated receptor which activates the KGA channel and a known activator for the other G-protein associated receptor; and

(c) detecting any change in KGA channel conductance, a decrease in KGA channel conductance indicating the identification of a nucleic acid molecule encoding the G-protein associated receptor capable of deactivating the KGA
5 channel.

37. An antibody directed against the channel of claim 18.

38. A monoclonal antibody of claim 37.

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FIGURE 1A

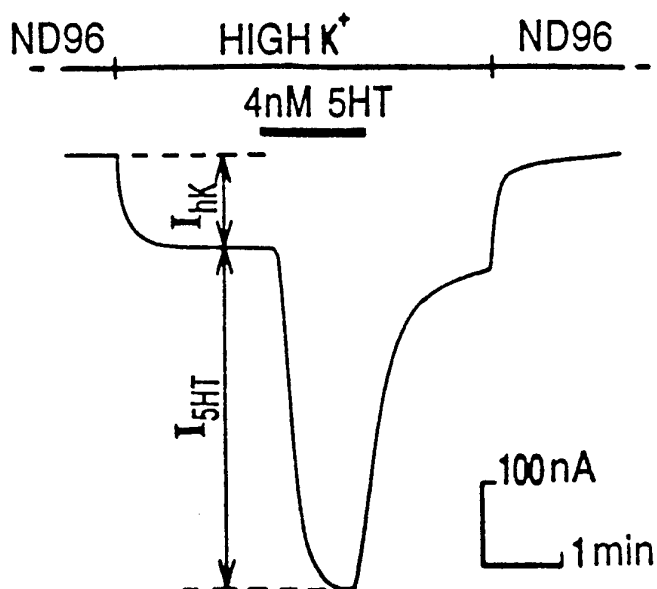


FIGURE 1B

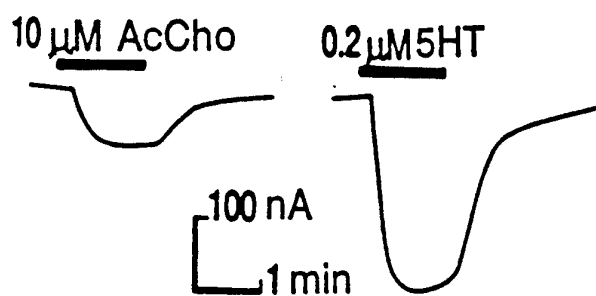


FIGURE 1C

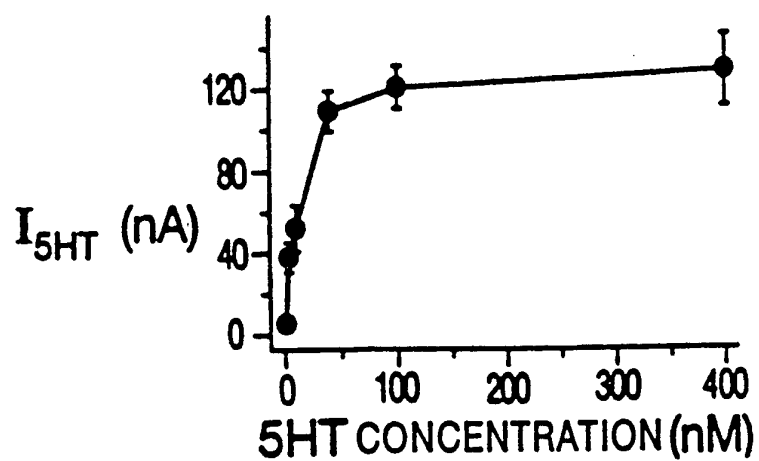
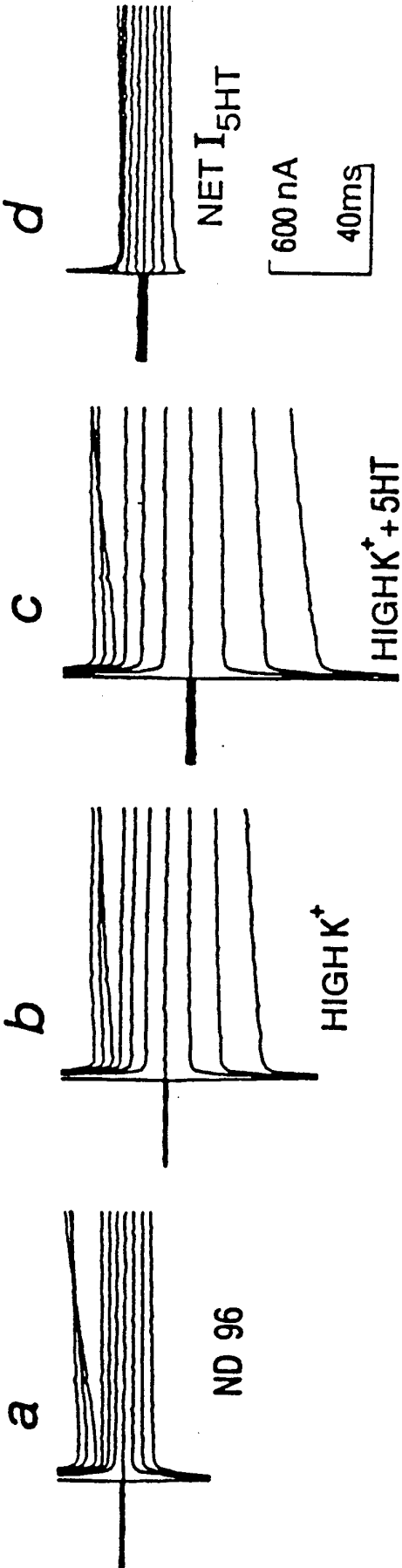


FIGURE 2A



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FIGURE 2B

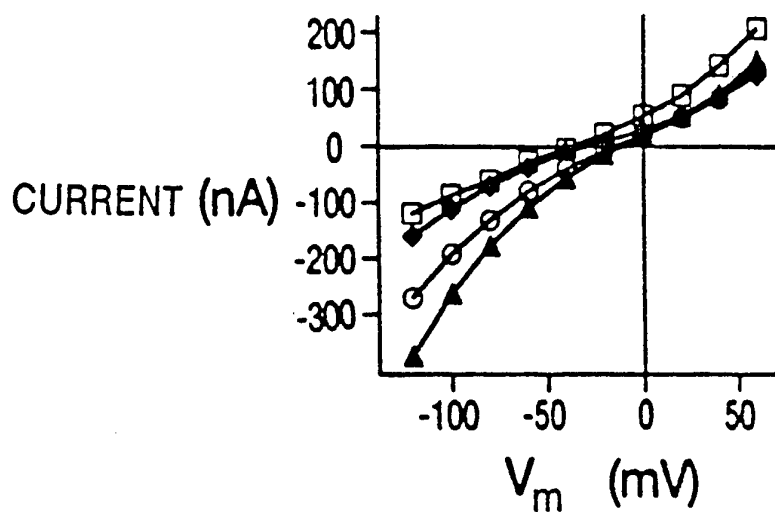


FIGURE 2C

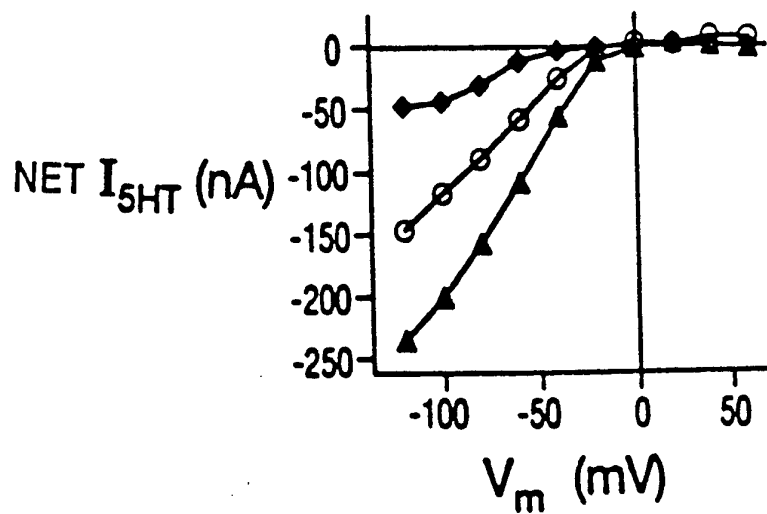
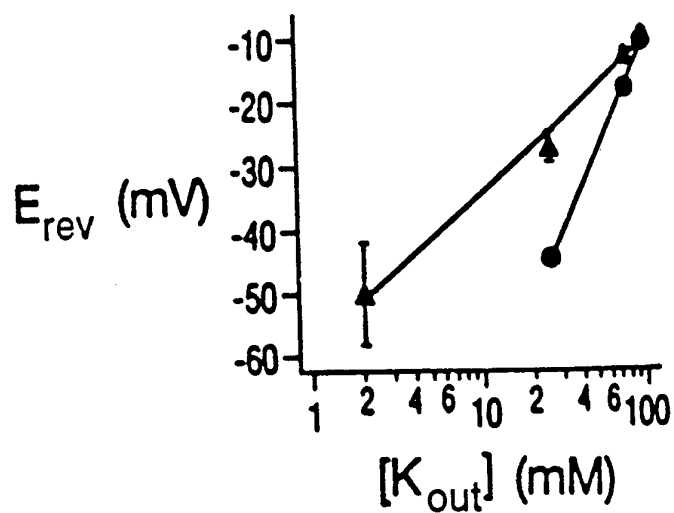


FIGURE 2D



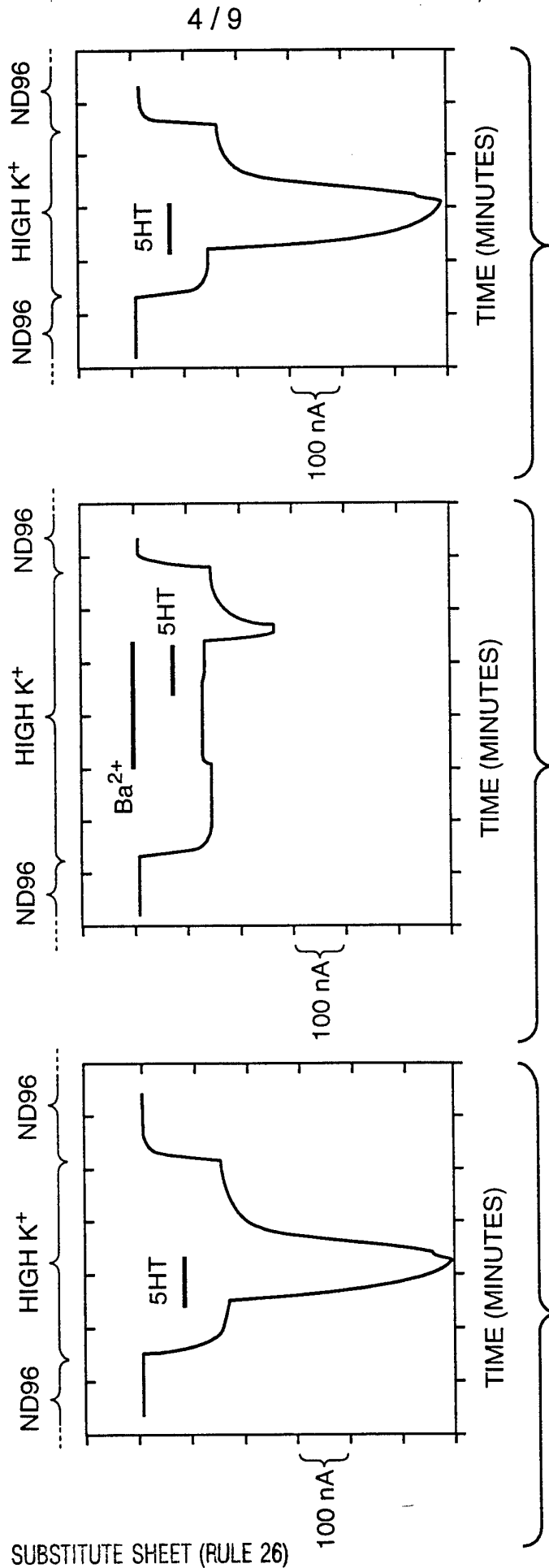


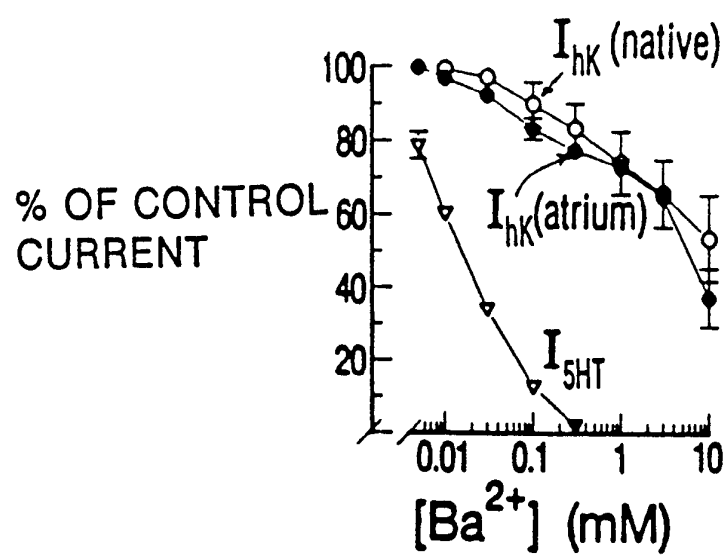
FIG. 3C

FIG. 3B

FIG. 3A

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FIGURE 3D



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FIGURE 4A

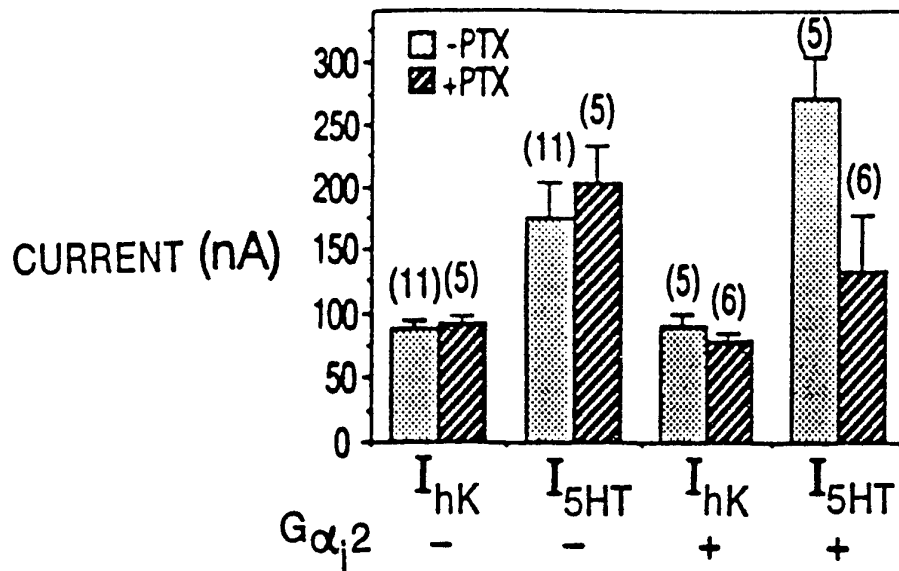
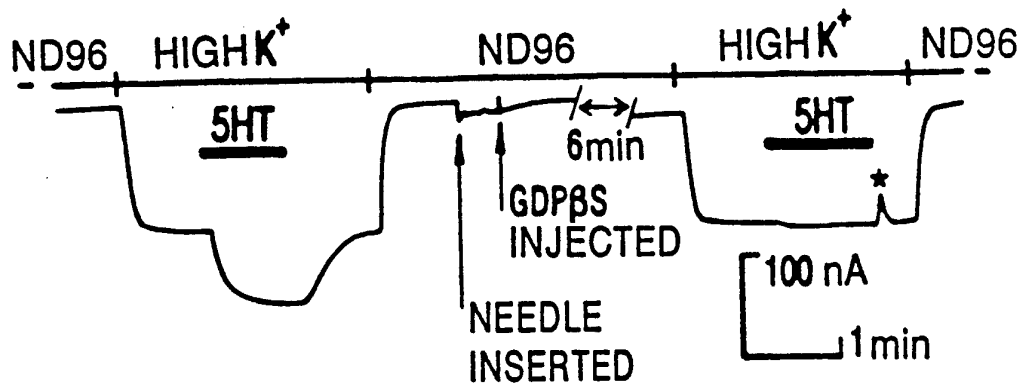


FIGURE 4B



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FIGURE 5 (1)

1	GGCA	CGA	GAA	TCT	GGA	TCT	CCC	CTC	CGT	ATT	ATG	TCT	GCA	CTC	CGA	46
1											M	S	A	L	R	5
47	AGG	AAA	TTT	GGG	GAC	GAT	TAC	CAG	GTA	GTG	ACC	ACT	TCG	TCC	AGC	91
6	R	K	F	G	D	D	Y	Q	V	V	T	T	S	S	S	20
92	GGT	TCG	GGC	TTG	CAG	CCC	CAG	GGG	CCA	GGA	CAG	GGC	CCA	CAG	CAG	136
21	G	S	G	L	Q	P	Q	G	P	G	Q	G	P	Q	Q	35
137	CAG	CTT	GTA	CCC	AAG	AAG	AAA	CGG	CAG	CGG	TTC	GTG	GAC	AAG	AAC	181
36	Q	L	V	P	K	K	K	R	Q	R	F	V	D	K	N	50
182	GGT	CGG	TGC	AAT	GTG	CAG	CAC	GGC	AAC	CTG	GGC	AGC	GAG	ACC	AGT	226
51	G	R	C	N	V	Q	H	G	N	L	G	S	E	T	S	65
227	CGC	TAC	CTT	TCC	GAC	CTC	TTC	ACT	ACC	CTG	GTG	GAT	CTC	AAG	TGG	271
66	R	Y	L	S	D	L	F	T	T	L	V	D	L	K	W	80
272	CGT	TGG	AAC	CTC	TTT	ATC	TTC	ATC	CTC	ACC	TAC	ACC	GTG	GCC	TGG	316
81	R	W	N	L	F	I	F	I	L	T	Y	T	V	A	W	95
317	CTC	TTC	ATG	GCG	TCC	ATG	TGG	TGG	GTG	ATC	GCT	TAT	ACC	CGG	GGC	361
96	L	F	M	A	S	M	W	W	V	I	A	Y	T	R	G	110
362	GAC	CTG	AAC	AAA	GCC	CAT	GTC	GGC	AAC	TAC	ACT	CCC	TGT	GTG	GCC	406
111	D	L	N	K	A	H	V	G	N	Y	T	P	C	V	A	125
407	AAT	GTC	TAT	AAC	TTC	CCC	TCT	GCC	TTC	CTT	TTC	TTC	ATC	GAG	ACC	451
126	N	V	Y	N	F	P	S	A	F	L	F	F	I	E	T	140
452	GAG	GCC	ACC	ATC	GGC	TAT	GGC	TAC	CGC	TAC	ATC	ACC	GAC	AAG	TGC	496
141	E	A	T	I	G	Y	G	Y	R	Y	I	T	D	K	C	155
497	CCC	GAG	GGC	ATC	ATC	CTT	TTC	CTT	TTC	CAG	TCC	ATC	CTT	GGC	TCC	541
156	P	E	G	I	I	L	F	L	F	Q	S	I	L	G	S	170
542	ATC	GTG	GAC	GCT	TTC	CTC	ATC	GGC	TGC	ATG	TTC	ATC	AAG	ATG	TCC	586
171	I	V	D	A	F	L	I	G	C	M	F	I	K	M	S	185
587	CAG	CCC	AAA	AAG	CGC	GCC	GAG	ACC	CTC	ATG	TTT	AGC	GAG	CAT	GCG	631
186	Q	P	K	K	R	A	E	T	L	M	F	S	E	H	A	200
632	GTT	ATT	TCC	ATG	AGG	GAC	GGA	AAA	CTC	ACT	CTC	ATG	TTC	CGG	GTG	676
201	V	I	S	M	R	D	G	K	L	T	L	M	F	R	V	215
677	GGC	AAC	CTG	CGC	AAC	AGC	CAC	ATG	GTC	TCC	GCG	CAG	ATC	CGC	TGC	721
216	G	N	L	R	N	S	H	M	V	S	A	Q	I	R	C	230
722	AAG	CTG	CTC	AAA	TCT	CGG	CAG	ACA	CCT	GAG	GGT	GAG	TTT	CTA	CCC	766
231	K	L	L	K	S	R	Q	T	P	E	G	E	F	L	P	245
767	CTT	GAC	CAA	CTT	GAA	CTG	GAT	GTA	GGT	TTT	AGT	ACA	GGG	GCA	GAT	811
246	L	D	Q	L	E	L	D	V	G	F	S	T	G	A	D	260
812	CAA	CTT	TTT	CTT	GTG	TCC	CCT	CTC	ACC	ATT	TGC	CAC	GTG	ATC	GAT	856
261	Q	L	F	L	V	S	P	L	T	I	C	H	V	I	D	275
857	GCC	AAA	AGC	CCC	TTT	TAT	GAC	CTA	TCC	CAG	CGA	AGC	ATG	CAA	ACT	901
276	A	K	S	P	F	Y	D	L	S	Q	R	S	M	Q	T	290

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FIGURE 5 (2)

902	GAA	CAG	TTC	GAG	GTG	GTC	GTC	ATC	CTG	GAA	GGC	ATC	GTG	GAA	ACC	946
291	E	Q	F	E	V	V	V	I	L	E	G	I	V	E	T	305
947	ACA	GGG	ATG	ACT	TGT	CAA	GCT	CGA	ACA	TCA	TAC	ACC	GAA	GAT	GAA	991
306	T	G	M	T	C	Q	A	R	T	S	Y	T	E	D	E	320
992	GTT	CTT	TGG	GGT	CAT	CGT	TTT	TTC	CCT	GTA	ATT	TCT	TTA	GAA	GAA	1036
321	V	L	W	G	H	R	F	F	P	V	I	S	L	E	E	335
1037	GGA	TTC	TTT	AAA	GTC	GAT	TAC	TCC	CAG	TTC	CAT	GCA	ACC	TTT	GAA	1081
336	G	F	F	K	V	D	Y	S	Q	F	H	A	T	F	E	350
1082	GTC	CCC	ACC	CCT	CCG	TAC	AGT	GTG	AAA	GAG	CAG	GAA	GAA	ATG	CTT	1126
351	V	P	T	P	P	Y	S	V	K	E	Q	E	E	M	L	365
1127	CTC	ATG	TCT	TCC	CCT	TTA	ATA	GCA	CCA	GCC	ATA	ACC	AAC	AGC	AAA	1171
366	L	M	S	S	P	L	I	A	P	A	I	T	N	S	K	380
1172	GAA	AGA	CAC	AAT	TCT	GTG	GAG	TGC	TTA	GAT	GGA	CTA	GAT	GAC	ATT	1216
381	E	R	H	N	S	V	E	C	L	D	G	L	D	D	I	395
1217	AGC	ACA	AAA	CTT	CCA	TCG	AAG	CTG	CAG	AAA	ATT	ACG	GGG	AGA	GAA	1261
396	S	T	K	L	P	S	K	L	Q	K	I	T	G	R	E	410
1262	GAC	TTT	CCC	AAA	AAA	CTC	CTG	AGG	ATG	AGT	TCT	ACA	ACT	TCA	GAA	1306
411	D	F	P	K	K	L	L	R	M	S	S	T	T	S	E	425
1307	AAA	GCC	TAT	AGT	TTG	GGT	GAT	TTG	CCC	ATG	AAA	CTC	CAA	CGA	ATA	1351
426	K	A	Y	S	L	G	D	L	P	M	K	L	Q	R	I	440
1352	AGT	TCG	GTT	CCT	GGC	AAC	TCT	GAA	GAA	AAA	CTG	GTA	TCT	AAA	ACC	1396
441	S	S	V	P	G	N	S	E	E	K	L	V	S	K	T	455
1397	ACC	AAG	ATG	TTA	TCA	GAT	CCC	ATG	AGC	CAG	TCT	GTG	GCC	GAT	TTG	1441
456	T	K	M	L	S	D	P	M	S	Q	S	V	A	D	L	470
1442	CCA	CCG	AAG	CTT	CAA	AAG	ATG	GCT	GGA	GGA	CCT	ACC	AGG	ATG	GAA	1486
471	P	P	K	L	Q	K	M	A	G	G	P	T	R	M	E	485
1487	GGG	AAT	CTT	CCA	GCC	AAA	CTA	AGA	AAA	ATG	AAC	TCT	GAC	CGC	TTC	1531
486	G	N	L	P	A	K	L	R	K	M	N	S	D	R	F	500
1532	ACA	TAG	CAA	AAC	ACC	CCA	TTA	GGC	ATT	ATT	TCA	TGT	TTT	GAT	TTA	1576
501	T	*														515
1577	GTT	TTA	GTC	CAA	TAT	TTG	GCT	GAT	AAG	ATA	ATC	CTC	CCC	GGG	AAA	1621
1622	TCT	GAG	AGG	TCT	ATC	CCA	GTC	TGG	CAA	ATT	CAT	CAG	AGG	ACT	CTT	1666
1667	CAT	TGA	AGT	GTT	GTT	ACT	GTG	TTG	AAC	ATG	AGT	TAC	AAA	GGG	AGG	1711
1712	ACA	TCA	TAA	GAA	AGC	TAA	TAG	TTG	GCA	TGT	ATT	ATC	ACA	TCA	AGC	1756
1757	ATG	CAA	TAA	TGT	GCA	AAT	TTT	GCA	TTT	AGT	TTT	CTG	GCA	TGA	TTT	1801
1802	ATA	TAT	GGC	ATA	TTT	ATA	TTG	AAT	ATT	CTG	GAA	AAA	TAT	ATA	AAT	1846
1847	ATA	TAT	TTG	AAG	TGG	AGA	TAT	TCT	CCC	CAT	AAT	TTC	TAA	TAT	ATG	1891
1892	TAT	TAA	GCC	AAA	CAT	GAG	TGG	ATA	GCT	TTC	AGG	GCA	CTA	AAA	TAA	1936
1937	TAT	ACA	TGC	ATA	CAT	ACA	TAC	ATG	CAT	ATG	CAC	AGA	CAC	ATA	CAC	1981

FIGURE 5 (3)

1982 ACA CAT ACT CAT ATA TAT AAA ACA TAC CCA TAC AAA CAT ATA TAT 2026
2027 CTA ATA AAA ATT GTG ATG TTT TGT TCA AAA AAA AAA AAA AAA AA 2070

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US94/05666

A. CLASSIFICATION OF SUBJECT MATTER

IPC(5) : C12N 15/12, 15/63, 5/16; C07K 13/00

US CL : 536/23.5; 435/320.1, 240.2, 69.1, 91; 530/395

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 536/23.5; 435/320.1, 240.2, 69.1, 91; 530/395

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

Please See Extra Sheet.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X -- Y -- A	<i>Nature</i> , Volume 303, issued 19 May 1983, B. Sakmann <i>et al.</i> , "Acetylcholine activation of single muscarinic K ⁺ channels in isolated pacemaker cells of the mammalian heart", pages 250-253, especially the abstract.	18-20, 22, 23, 29 ----- 37, 38 ----- 21, 24-28, 31-36
X -- Y -- A	<i>Science</i> , Volume 235, issued 09 January 1987, A. Yatani <i>et al.</i> , "Direct Activation of Mammalian Atrial Muscarinic Potassium Channels by GTP Regulatory Protein G _k ", pages 207-211, especially the abstract.	18-20, 22, 23, 29 ----- 37, 38 ----- 21, 24-28, 31-36

☒ Further documents are listed in the continuation of Box C.
 ☐ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier document published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

17 AUGUST 1994

Date of mailing of the international search report

02 SEP 1994

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/05666

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X -- Y -- A	<i>Proceedings of the National Academy of Sciences of the USA</i> , Volume 88, issued July 1991, A. Karschin <i>et al.</i> , "Heterologously expressed serotonin 1A receptors couple to muscarinic K ⁺ channels in heart", pages 5694-5698, especially the abstract.	18-20, 22, 23, 29 ----- 37, 38 ----- 21, 24-28, 31-36
X,P ---- Y,P	<i>Nature</i> , Volume 364, Number 6440, issued 26 August 1993, Y. Kubo <i>et al.</i> , "Primary structure and functional expression of a rat G-protein coupled muscarinic potassium channel", pages 802-806, especially the abstract and Fig. 1.	1-12, 17-20 ----- 37, 38
X,P ---- Y,P ---- A,P	<i>Proceedings of the National Academy of Sciences of the USA</i> , Volume 90, issued November 1993, N. Dascal <i>et al.</i> , "Atrial G protein-activated K ⁺ channel: Expression cloning and molecular properties", pages 10235-10239, especially the abstract and Figs. 1A and 2.	1-12, 17-20 ----- 13-16, 37, 38 ----- 21-36
A,P	<i>Proceedings of the National Academy of Sciences of the USA</i> , Volume 90, issued July 1993, N. Dascal <i>et al.</i> , "Expression of an atrial G-protein-activated potassium channel in <i>Xenopus</i> oocytes", pages 6596-6600.	1-38
A	<i>Nature</i> , Volume 362, Number 6416, issued 11 March 1993, R. Aldrich, "Potassium channels: Advent of a new family", pages 107-108.	1-38
A	<i>Nature</i> , Volume 362, issued 04 March 1993, K. Ho <i>et al.</i> , "Cloning and expression of an inwardly rectifying ATP-regulated potassium channel", pages 31-38.	1-38
A	<i>Nature</i> , Volume 362, Number 6416, issued 11 March 1993, Y. Kubo <i>et al.</i> , "Primary structure and functional expression of a mouse inward rectifier potassium channel", pages 127-133.	1-38

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/05666

Box I Observations where certain claims were found unsearchable (Continuation of item 1 of first sheet)

This international report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box II Observations where unity of invention is lacking (Continuation of item 2 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

- I. Claims 1-26, 37, and 38, directed to inward-rectifying "KGA" potassium channels, corresponding DNAs, (m)Abs specific for them, and screening assays utilizing such channels.
- II. Claims 27-36, directed to methods to identify and isolate G-protein coupled receptor cDNAs which are capable of activating or deactivating KGA channels, and to the protein products of such cDNAs.

(continued on supplemental sheet)

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
☒ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/05666

B. FIELDS SEARCHED

Electronic data bases consulted (Name of data base and where practicable terms used):

Keyword databases: USPTO-APS, Dialog (Medline, Biosis, CAS, SciSearch Derwent WPI)

Search terms: potassium/K+ channel; inward rectif?; muscarinic

Sequence databases: IgSuite (searched with sequences in US priority application)

Box II Observations where unity of invention is lacking (continued).

The special technical feature of group I which defines an advance over the art is a recombinant KGA potassium channel. The special technical feature of group II is the activating or deactivating interaction of certain G-protein coupled cellular receptors with the KGA channel. These special technical features define distinct advances over the art because each is related to the other by application of an inventive step (i.e., neither is necessarily obvious over the other); furthermore, the (de)activating receptors of group II can be identified using naturally isolated KGA receptors and in vitro assays which do not require the use of the recombinant receptors of group I. The inventions of groups I and II are therefore not considered to be so linked as to form a single general inventive concept within the meaning of PCT Rule 13.