

(19) World Intellectual Property
Organization
International Bureau



(43) International Publication Date
16 September 2004 (16.09.2004)

PCT

(10) International Publication Number
WO 2004/079337 A2

- (51) International Patent Classification⁷: **G01N** (74) Agent: FEIT, Irving, N.; Hoffmann & Baron, LLP, 6900 Jericho Turnpike, Syosset, NY 11791 (US).
- (21) International Application Number: PCT/US2004/005962 (81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BW, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NA, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.
- (22) International Filing Date: 27 February 2004 (27.02.2004)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
10/377,139 1 March 2003 (01.03.2003) US (84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).
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- Published:**
— without international search report and to be republished upon receipt of that report
- For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

(54) Title: VOLTAGE SENSOR DOMAINS OF VOLTAGE-DEPENDENT ION CHANNEL PROTEINS AND USES THEREOF

(57) Abstract: A composition of matter suitable for use in identifying chemical compounds that bind to voltage-dependent ion channel proteins, the composition comprising a screening protein that comprises an ion channel voltage sensor domain of the ion channel protein immobilized on a solid support.



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VOLTAGE SENSOR DOMAINS OF VOLTAGE-DEPENDENT ION CHANNEL PROTEINS AND USES THEREOF

[0001] This application asserts priority to U.S. Application Serial No. 10/377,139 filed on March 1, 2003. The specification of U.S. Application Serial No. 10/377,139 is hereby incorporated by reference in its entirety.

[0002] The invention described in this application was made with funds from the National Institutes of Health, Grant Number GM43949 and GM47400. The United States government has certain rights in this invention.

BACKGROUND OF THE INVENTION

[0003] Many cells produce electrical impulses known as electrical activities (e.g., action potential) that propagate across their surface membrane. Action potentials travel quickly, and their arrival at a distant location initiates cellular processes such as the release of neurotransmitter molecules or the contraction of muscles (Hille B. *Ion Channels of Excitable Membranes*. Sinauer Associates, Inc. Sunderland, MA, 2001). These electrical impulses are the means by which living cells transfer information over large distances in short time intervals.

[0004] Action potential theory contains two key elements (Hodgkin et al. *J. Physiol. (Lond)* 1952, 117:500-544). The first element is that the membrane of a cell can undergo transient changes in its selective permeability to, for example, Na^+ and K^+ ions. The second element is that the permeability changes depend on membrane voltage. These two elements create an interesting situation because selective permeability to ions determines the membrane voltage, while the voltage determines the permeability.

[0005] The family of protein molecules known as the voltage-dependent cation channels typically mediate electrical activity. This family includes potassium (K^+), sodium (Na^+) and calcium (Ca^{2+}) selective members. The opening of a pore of a voltage-dependent ion channel, a process known as gating, is dependent upon the membrane voltage. When the pore of a voltage-dependent cation channel opens, it selectively conducts predominantly its namesake ion.

[0006] It is believed that charged amino acids, called gating charges, move through the membrane electric field before the pore opens, allowing membrane voltage to bias the equilibrium between closed and opened conformations (Armstrong et al. *J. Gen. Physiol.* 1974, 63:533-552; Sigworth et al. *Q. Rev. Biophys.* 1994, 27:1-40; and Bezanilla *Physiol. Rev.* 2000, 80:555-592).

[0007] In K^+ channels, the gating charge per tetrameric channel corresponds to 12-14 electron charges (3.0-3.5 charges per subunit) crossing the entire membrane voltage difference. This large gating charge gives rise to a steep change in open probability as a function of membrane voltage.

[0008] All members of the voltage-dependent cation channel family typically contain six hydrophobic segments, S1 through S6 (S1-S6) (see figures 1 and 2), per subunit. Four subunits (most often identical in K^+ channels and linked together as homologous 'domains' in Na^+ and Ca^{2+} channels) surround a central ion conduction pore. S5 through S6 line the pore and determine ion selectivity, while S1 through S4 form the voltage sensors. Certain charged amino acids within the voltage sensors account for most of the gating charge. These amino acids are particularly the first four arginines in S4.

[0009] Voltage-dependent ion channels are present in every cell and are involved in generation of electrical activity and information processing. As such, aberrant electrical activity can result in various conditions, such as heart arrhythmias, epilepsy, hypertension, etc.

[0010] There is a need for a composition and method for rapidly screening chemical compounds to determine whether the compounds bind to voltage-dependent ion channels.

SUMMARY OF THE INVENTION

[0011] In one embodiment, the invention relates to a composition of matter suitable for use in identifying chemical compounds that bind to voltage-dependent ion channel proteins. The composition comprises a screening protein that comprises an ion channel voltage sensor domain of the ion channel protein immobilized on a solid support.

[0012] In another embodiment, the invention relates to a kit suitable for use in identifying chemical compounds that bind to voltage-dependent ion channel proteins. The kit comprises a screening protein that comprises an ion channel voltage sensor domain of the ion channel protein and a solid support.

[0013] In another embodiment, the invention relates to a labeled screening protein suitable for use in identifying chemical compounds that bind to a voltage-dependent ion channel protein. The labeled screening protein comprising an ion channel voltage sensor domain of the ion channel protein and a detectable label.

[0014] In another embodiment, the invention relates to a method for screening for drug candidates that target voltage dependent ion channel protein. The method comprises providing a screening protein, contacting the screening protein with a chemical compound, determining whether the chemical compound binds to the screening protein, wherein chemical compounds that bind to the screening protein are drug candidates.

BRIEF DESCRIPTION OF THE FIGURES

[0015] Figure 1. Sequences of prokaryotic and eukaryotic voltage-dependent potassium (Kv) channels. Regions of high homology are colored in grey; functionally important residues are colored dark grey. Alignment was made with ClustalW followed by manual adjustment and exclusion of loops. The potassium channels are: *Apernix*, *Aeropyrum pernix* (Genbank Accession number GI: 5104624); *Paeru*, *Pseudomonas aeruginosa* (Genbank Accession number GI: 15596693); *Dradio*, *Deinococcus radiodurans* (Genbank Accession number GI: 15805856); *Shaker*, *Drosophila melanogaster* (Genbank Accession number GI: 13432103); *RatKv2.1*, *Rattus norvegicus* (Genbank Accession number GI: 24418849); *HsapKv4.3*, *Homo sapiens* (Genbank Accession number GI: 5059060). The sequences corresponding to the above Genbank Accession numbers are hereby incorporated by reference.

[0016] Figure 2. Architecture of a voltage-dependent potassium channel. A) Transmembrane-spanning segments (S1–S6) are labelled; B) four subunits surround the pore. S1–S4 form the voltage sensor and S5–S6, including P, form the pore, represented by the KcsA potassium channel structure (backbone model).

[0017] Figure 3. Functional and structural analysis of the isolated voltage sensor domain. A) The isolated voltage sensor retains its ability to bind tarantula toxins that specifically inhibit voltage sensors. Quantitative reverse phase HPLC chromatogram of toxins eluted from a Co^{2+} affinity column in the presence (top) or absence (bottom) of the voltage sensor domain. B) VSTX1, eluted at the position marked with an arrow (in Figure 3A), binds to the domain and inhibits KvAP channel currents elicited by a +100 mV depolarization.

DETAILED DESCRIPTION OF THE INVENTION

[0018] The invention is based on the surprising discovery by the inventors that a protein comprising a voltage sensor domain of a voltage-dependent ion channel protein retains its native structure, even when immobilized on a solid support. Such a protein is herein referred to as a screening protein. If the ion channel protein is full-length, the ion selectively is retained after reconstitution into planar lipid bilayers.

[0019] In one embodiment, the invention relates to a composition of matter suitable for use in screening chemical compounds in order to identify drug candidates that bind to voltage-dependent ion channel proteins. The composition comprises a voltage-dependent ion channel protein immobilized on a solid support. The protein may contain additional components often found on proteins, such as glycosylation units, lipids, sulfur groups, and phosphate groups.

[0020] Voltage-dependent ion channel proteins are selective for particular ions. Such ions include, for example, potassium, sodium, and calcium. Thus, the ion channel protein can be a potassium ion channel protein, a sodium ion channel protein, or a calcium ion channel protein.

[0021] The amino acid sequence of a voltage-dependent ion channel protein across species is highly conserved. Thus, the ion channel protein can be from an organism of any species.

[0022] For example, the species can be a prokaryotic organism. Some examples of prokaryotic organisms include archaeobacteria and bacteria. An example of an archaeobacteria is *Aeropyrum pernix*. Examples of bacteria include *Pseudomonas aeruginosa* and *Deinococcus radiodurans*. Preferably, the ion channel protein is an *Aeropyrum pernix* (Apernix) ion channel protein, such as KvAP. The amino acid sequence of Apernix KvAP is shown in Figure 1.

[0023] Alternatively, the species can be a eukaryotic organism. Examples of eukaryotic organisms include invertebrates, vertebrates, and mammals. Examples of invertebrates include insects, such as *Drosophila melanogaster* and mollusks. Examples of vertebrates include mammals, reptiles, and fish. Mammals include, for example, dogs, cats, horses, sheep, cows, rats, such as *Rattus norvegicus*, mice, and primates, including humans (i.e., *Homo sapiens*). The preferred eukaryotic ion channel protein is a *Homo sapien* ion channel protein.

[0024] The amino acid sequence homology for voltage-dependent potassium channel proteins of *Aeropyrum pernix*, *Pseudomonas aeruginosa*, *Deinococcus radiodurans*, *Drosophila melanogaster*, *Rattus norvegicus* and *Homo sapiens* is compared in Figure 1. These amino acid sequence were predicted from the corresponding nucleic acid sequences disclosed in Genbank. The accession numbers are given in the brief description of Figure 1 above.

[0025] The Genbank accession numbers of nucleic acid sequences that encode some calcium and sodium channel proteins, as well as some additional potassium channel proteins, are listed below.

[0026] Some examples of Genbank Accession numbers for voltage-dependent calcium channels include *Rattus norvegicus* calcium channel, voltage-dependent, T type, alpha 1G subunit, mRNA, Genbank Accession number GI:24429575; *Homo sapiens* calcium channel, voltage-dependent, alpha 1I subunit(CACNA1I) mRNA, Genbank Accession number GI:21361076; *Mus musculus* calcium channel, voltage-dependent, L type, alpha 1C subunit (Cacna1c), mRNA, Genbank Accession number GI:6753227; *Homo sapiens* calcium channel, voltage-dependent, alpha 1G subunit (CACNA1G), mRNA, Genbank Accession number GI:20070162; and *Caenorhabditis elegans* calcium Channel, Alpha subunit CCA-1 (210.2 kD) (cca-1) mRNA, Genbank Accession number GI:25146600.

[0027] Some examples of Genbank Accession numbers for voltage-dependent sodium channels include *Rattus norvegicus* sodium channel, voltage-gated, type11, alpha polypeptide (Scn11a), mRN, Genbank Accession number GI:15011860; *Homo sapiens* sodium channel, voltage-gated, type I, alpha polypeptide (SCN1A), mRNA, Genbank Accession number GI:21914835; *Rattus norvegicus* sodium channel, voltage-gated, type 8, alpha polypeptide (Scn8a), mRNA, Genbank Accession number GI:9507066; *Mus musculus* sodium channel,

voltage-gated, type XI, alpha polypeptide (Scn11a), mRNA, Genbank Accession number GI:6755405; and *Bos taurus* mRNA for voltage-gated sodium channel alpha subunit, Genbank Accession number GI:18477464.

[0028] Some examples of Genbank Accession numbers for voltage-dependent potassium channels include *D. melanogaster* ShB1 mRNA for Shaker gene, Genbank Accession number GI:288441; *Homo sapiens* potassium voltage-gated channel, Shab-related subfamily, member 1 (KCNB1), mRNA, Genbank Accession number GI:27436972; *Oryctolagus cuniculus* voltage-gated potassium channel Kv2.1 (KCNB1) mRNA, complete cds, Genbank Accession number GI:8572238; *Xenopus laevis* Kv3.1 potassium channel mRNA, complete cds, Genbank Accession number GI:5817539; and *Xenopus laevis* maxi-K potassium channel alpha subunit Slo mRNA, complete cds, Genbank Accession number GI:14582151.

[0029] All the sequences corresponding to the above listed Genbank Accession numbers are hereby incorporated by reference.

[0030] As can be seen from figures 1 and 2, an entire ion channel protein comprises (i) a voltage sensor domain and (ii) an ion-selective pore domain which includes a selectivity filter. The ion voltage sensor domain comprises segments S1-S4. The ion-selective pore domain, also referred to herein as an ion conduction pore, comprises segments S5-S6. As used herein, when reference is made to segments S5-S6, it includes segment P. Segment P occurs between segment S5 and segment S6. The selectivity filter comprises the signature sequence amino acids between segment P and segment S6.

[0031] The screening protein useful in the present invention comprises an ion channel voltage sensor domain. For example, the screening protein can comprise the entire ion channel protein. Preferably, the screening protein includes only (i.e., consists of) the ion channel voltage sensor domain, i.e., segments S1-S4, and excludes an ion conduction pore (i.e., segments S5-S6, including segment P).

[0032] In a more preferred embodiment, the screening protein comprises an amino acid sequence that consists essentially of the voltage sensor domain, i.e., includes segments S1-S4, and one or more additional amino acid residues that do not change the essential nature of the

voltage sensor domain. The number of additional amino acid residues is preferably relatively small. In order to constitute a relatively small number of amino acids, the number of amino acid residues should not exceed approximately 100, preferably approximately 50, and more preferably approximately 10 amino acid residues. The additional amino acid residues may, for example, be relics of the method of isolating the voltage sensor domains

[0033] In addition, one or more amino acid residues may be added to the screening protein for a specific purpose. For example, amino acids may be added for the purpose of labeling the screening protein or for attachment of the screening protein to a solid support. Examples of an amino acid sequence for attaching screening proteins to a solid support include hexahistidine (e.g., Co^{2+} column) and glutathione S-transferase.

[0034] The optional amino acids can be attached anywhere on the screening protein. Preferably, the optional amino acids are attached to either the N-terminus or C-terminus. The optional amino acids may also be added to any internal residue in the sequence of the screening protein, as long as the optional amino acids do not disrupt the native structure of the screening protein.

[0035] The screening protein can be a monomer or a polymer. Examples of polymers include dimers, trimers, tetramers, etc. There is no limit to the number of subunits that can polymerize, although screening proteins are typically not larger than tetramers.

[0036] The screening protein can be a functional analog of a naturally occurring voltage-dependent ion channel protein. An analog can, for example, be a substitution or deletion mutant of the ion channel protein. Substitutions and deletions can be made as long as the screening protein continues to satisfy the function of the voltage-dependent ion channel protein described herein.

[0037] Preferably, any substitutions of amino acids in a screening protein are conservative, i.e., within a group of amino acids having similar physicochemical characteristics. Amino acids may be grouped according to their physicochemical characteristics as follows:

- (a) Non-polar amino acids: Ala(A) Ser(S) Thr(T) Pro(P) Gly(G);
- (b) Acidic amino acids: Asn(N) Asp(D) Glu(E) Gln(Q);

- (c) Basic amino acids: His(H) Arg(R) Lys(K);
- (d) Hydrophobic amino acids: Met(M) Leu(L) Ile(I) Val(V); and
- (e) Aromatic amino acids: Phe(F) Tyr(Y) Trp(W).

[0038] During expression, the first five N-terminal amino acids may be replaced by a single leucine residue. Therefore, a screening protein where the first five N-terminal amino acids are replaced by a single leucine residue is considered to be a functional analog.

[0039] In one embodiment, the screening protein is immobilized on a solid support. The screening protein may be attached to the solid support by any method known in the art, and by any type of bond. The bond can be a covalent bond or a non-covalent bond. An example of a non-covalent bond is a hydrogen bond.

[0040] The solid support can be any support that is capable of immobilizing the screening protein. Examples of solid supports include a resin, a microtitre plate, and nitrocellulose paper. The resin may, for example, comprise cobalt, nickel, nickel-NTA agarose, and glutathione sepharose.

[0041] In another embodiment, the invention relates to a labeled screening protein suitable for use in identifying chemical compounds that bind to voltage-dependent ion channel proteins. The labeled screening protein comprises an ion channel voltage sensor domain of the ion channel protein and a detectable label. The screening protein may be any of the screening proteins described herein.

[0042] Methods for preparing a labeled protein are well known in the art. Some examples are described below.

[0043] The label may be radioactive. Some examples of useful radioactive labels include ^{32}P , ^{125}I , ^{131}I , ^{35}S , ^{14}C , and ^3H . Use of radioactive labels have been described in U.K. 2,034,323, U.S. 4,358,535, and U.S. 4,302,204.

[0044] Some examples of non-radioactive labels include enzymes and chromophores. Useful enzymatic labels include enzymes that cause a detectable change in a substrate. Some useful enzymes and their substrates include, for example, horseradish peroxidase (pyrogallol and

o-phenylenediamine), beta-galactosidase (fluorescein beta-D-galactopyranoside), and alkaline phosphatase (5-bromo-4-chloro-3-indolyl phosphate/nitro blue tetrazolium). The use of enzymatic labels have been described in U.K. 2,019,404, EP 63,879, in Ausubel, F.M. et al. (Eds.), Rotman 1961. *Proc. Natl. Acad. Sci. USA* 47:1981-1991, and by Current Protocols in Molecular Biology, John Wiley & Sons, Inc., New York (1999).

[0045] Useful chromophores include, for example, fluorescent, chemiluminescent, and bioluminescent molecules, as well as dyes. Some specific chromophores useful in the present invention include, for example, fluorescein, rhodamine, Texas red, phycoerythrin, umbelliferone, luminol.

[0046] In another embodiment, the invention relates to a kit suitable for use in identifying chemical compounds that bind to voltage-dependent ion channel proteins. The kit comprises a screening protein that comprises an ion channel voltage sensor domain of the ion channel protein and a solid support. The screening protein can comprise any screening protein described herein. The solid support present in the kit can be any support described herein.

[0047] The kit may further contain optional components that are helpful in preparing reagents and carrying out procedures described herein. Some examples of optional components include labels, buffers, etc.

[0048] In another embodiment, the invention relates to a method for screening for drug candidates that target voltage-dependent ion channels. The first step in the method is providing a screening protein. Methods for preparing screening proteins by expression of the DNA encoding a screening protein in a host cell are described below.

[0049] The screening protein is contacted with a chemical compound. The chemical compound can be any molecule. Examples of molecules include biological molecules and small molecules. The chemical compounds can be a mixture of one or more different chemical compounds.

[0050] A biological molecule is any molecule which contains a polyamino acid, a polynucleotide, or a polysaccharide, and has a molecular weight greater than 450. Polyamino acids include proteins, polypeptides, and peptides.

[0051] Small molecules are typically organic compounds, including organometallic and organosilicon compounds, and the like, and generally have molecular weights of approximately 450 or less. Small molecules can further include molecules that would otherwise be considered biological molecules, except their molecular weight is not greater than 450. Thus, small molecules can include, monosaccharides, oligosaccharides, amino acids, oligopeptides, nucleotides, oligonucleotides, and their derivatives, having a molecular weight of 450 or less.

[0052] It is emphasized that a small molecule can have any molecular weight. They are merely called small molecules because they do not qualify as biological molecules, and typically have molecular weights less than 450.

[0053] The screening protein can be contacted with the chemical compound by any method known to those in the art. Preferably, either the screening protein or the chemical compound is immobilized on a solid support.

[0054] For example, the screening protein may be immobilized on a resin. The screening protein can be contacted with the chemical compound by eluting the chemical compound through a column containing the screening protein immobilized on the resin.

[0055] Alternatively, the chemical compound may be immobilized on a microtitre plate. The screening proteins can be contacted with the chemical compound by incubating the plate with the chemical compound. Many chemical compounds may be immobilized on a plate, thereby allowing the rapid screening of the compounds.

[0056] The next step in screening is to determine whether the chemical compound binds to the screening proteins. Binding can be determined by any method known in the art.

[0057] For example, a label may be bound to the chemical compound or to the screening protein, depending on which is immobilized to the solid support. Usually, the component that is not immobilized is the component that is labeled. Thus, if the screening protein is immobilized, the chemical compound is labeled. If the chemical compound is immobilized, the screening protein is labeled.

[0058] After contacting the chemical compounds and the screening proteins as described above, detection of an immobilized label indicates the binding of screening proteins to a chemical compound. Such chemical compounds are drug candidates that target voltage dependent ion channel proteins.

[0059] Preferably, the drug candidate alters the function of the voltage dependent ion channel proteins, typically by causing the ion channel proteins either to stay open or to stay closed. For example, a drug candidate that causes the ion channel protein to stay closed inhibits the ion channel proteins. Any assay known to those in the art can be used to determine whether a drug candidate alters voltage dependent ion channels. An example of an assay is an electrophysiological assay described in, for instance, Example 2, see below.

[0060] Electrical activity, (i.e., cellular electrical activity), whether normal or aberrant, is generated by voltage dependent ion channels, and therefore can be influenced by agents that affect voltage dependent ion channels. The drug candidate may be useful for treating any condition mediated by aberrant electrical activity, such as the magnitude of the resting membrane voltage, or shape and frequency of the action potential.

[0061] The condition can be, for example, asthma, hypertension, arrhythmia, epilepsy, nerve conduction abnormalities, atrial fibrillation, conditions associated with immune abnormalities due to, for instance, inappropriate lymphocyte stimulation, conditions associated with abnormalities of fluid and/or electrolyte secretion by, for example, epithelial membranes, such as in cystic fibrosis, and conditions associated with abnormal excretion by the renal system, such as in certain nephropathies, etc. Aberrant electrical activity can also initiate uptake or release of neurotransmitters, or initiate contraction of muscles.

[0062] The aberrant electrical activity can occur in any cell, organ or system in a body. Examples of cells include nerve cells, such as neurons, glial cell, and dendrites. Examples of organs and systems include heart, brain, lung, kidney, liver, muscle, digestive system, and peripheral nervous system. The muscle can be cardiac, skeletal, or smooth muscle.

[0063] The neurotransmitter can be any neurotransmitter. Examples of neurotransmitters include dopamine, epinephrine and norepinephrine.

[0064] Neurotransmitters are generally either excitatory neurotransmitters or inhibitory neurotransmitters. Excitatory neurotransmitter typically open cation channels, causing an influx of, for example, sodium, which depolarizes the postsynaptic membrane for firing an action potential. Examples of excitatory neurotransmitters include acetylcholine, glutamate, and serotonin.

[0065] Alternatively, inhibitory neurotransmitters usually suppresses firing of an action potential by keeping postsynaptic membranes polarized. Examples of inhibitory neurotransmitters include γ -aminobutyric acid and glycine.

[0066] These candidate drugs can be further tested for activity against a condition mediated by an aberrant electrical activity by methods known to those in the art. For example, the further testing can be those that are routinely done by clinicians and physicians during pre-clinical and clinical trials.

General Methods and Assays

[0067] The screening proteins may be prepared by methods that are well known in the art. Some general methods and techniques are described below. More specific methods and techniques are found in the specific examples below.

[0068] One method for producing screening proteins includes isolating or synthesizing DNA encoding the screening protein, and producing the recombinant protein by expressing the DNA, optionally in a recombinant vector, in a suitable host cell.

[0069] The proteins may also be made synthetically, i.e. from individual amino acids, or semisynthetically, i.e. from oligopeptide units or a combination of oligopeptide units and individual amino acids. Suitable methods for synthesizing proteins are described by Stuart and Young in "Solid Phase Peptide Synthesis," Second Edition, Pierce Chemical Company (1984), Solid Phase Peptide Synthesis, Methods Enzymol., 289, Academic Press, Inc, New York (1997).

[0070] Nucleic acids encoding the proteins may also be synthesized *in vitro*. Suitable methods for synthesizing DNA are described by Caruthers et al. 1985. *Science* 230:281-285 and

DNA Structure, Part A: Synthesis and Physical Analysis of DNA, Lilley, D.M.J. and Dahlberg, J.E. (Eds.), Methods Enzymol., 211, Academic Press, Inc., New York (1992).

[0071] Nucleic acid molecules encoding the ion channel proteins may be designed or assembled from known nucleic acid sequences encoding the ion channel proteins. The nucleic acid sequences may be obtained by those skilled in the art from collections of nucleic acid sequences, such as GenBank.

[0072] Alternatively, the nucleic acid sequence may be derived from a known amino acid sequence of an ion channel protein using the genetic code, as is routine to those of skill in the art. The nucleic acid sequence may then be synthesized as described above. Similarly, the amino acid sequences of the screening proteins may be derived from the corresponding nucleic acid sequence.

[0073] The methods, constructs and host cells suitable for production of screening proteins in standard small-scale culture systems, as well as large-scale production systems, include fermenter systems, hollow fiber culture systems, tumbler systems, and suspension culture systems to name but a few.

[0074] Methods and procedures for the manipulation of nucleic acids, polymerase chain reaction (PCR) methods for amplification of nucleic acids, construction of expression vectors, transformation of host cells, and the culture of transformed cells for the production of protein are known. These and many more relevant methods may be found in a variety of laboratory manuals, texts and guides. For a general guide, see, for instance, Sambrook & Russel, (2001) Molecular Cloning, Third edition, Cold Spring Harbor Press. Other useful sources include: Ausubel et al., 1992 Short Protocols in Molecular Biology, Second edition, John Wiley & Son; Gene Expression Technology, Methods in Enzymology Vol. 185 (ed. David Goeddel et al., Academic Press, Inc., London, 1991); Gene Structure and Expression, Second Edition, J. D. Hawkins (Cambridge University Press, London, 1991); PCR Protocols: A Guide to Methods and Applications (Innis, et al. 1990, Academic Press, San Diego, Calif.); Methods in Molecular Biology (Vol. 7), Gene Transfer and Expression Protocols, (ed. E. J. Murray, 1991, The Humana Press Inc., Clifton, N.J.).

[0075] The nucleic acid encoding screening proteins may be replicated and expressed in a suitable host cell. Suitable host cells include prokaryotic host cells and eukaryotic host cells. Suitable prokaryotic host cells include *E. coli* cells which are preferred. Suitable eukaryotic host cells include yeast cells, insect cells and mammalian cells, the latter being preferred.

[0076] Screening proteins are expressed in eukaryotic hosts in preference to prokaryotic hosts in cases where the protein must be post-transcriptionally modified. Examples of post-transcriptional modification include glycosylation, phosphorylation, disulfide bond formation, oligomerization and specific cleavage of the transcribed protein product.

[0077] Prokaryotic hosts do not perform certain post-transcriptional modifications of ion channel proteins, such as for instance glycosylation. For this reason expression in eukaryotic systems is preferred despite the higher costs associated with production of biologics in eukaryotic systems as compared with the costs of biologics produced in prokaryotic host systems.

[0078] Prokaryotic host systems are preferred for expression and production of screening proteins of the invention that do not require post-transcriptional modifications that are unique to eukaryotic systems and where the screening proteins are correctly folded or may be refolded *in vitro*.

[0079] Many standard well known cloning and expression and isolation/purification techniques that reflect the state of the art in recombinant DNA and protein methods are described in detail in Sambrook & Russel, *Molecular Cloning: A Laboratory Manual*, Third Edition, Cold Spring Harbor Laboratory Press, Cold Spring Harbor, NY (2001). Techniques for expression of cloned genes in *E. coli* and in mammalian cells is described in detail in Chapters 15 and 16-17, respectively of the Sambrook & Russel Laboratory Manual (Id).

Labels

[0080] The labels may be conjugated to the screening protein or chemical compound by methods that are well known in the art. The labels may be directly attached through a functional group on the screening protein or chemical compound. The screening protein or chemical compound either contains or can be caused to contain such a functional group. Some examples

of suitable functional groups include, for example, amino, carboxyl, sulfhydryl, maleimide, isocyanate, isothiocyanate.

[0081] Alternatively, labels such as enzymes and chromophoric molecules may be conjugated to the screening protein or chemical compound by means of coupling agents, such as dialdehydes, carbodiimides, dimaleimides, and the like.

EXAMPLES

Example 1: Preparation of *Aeropyrum pernix* KvAP.

[0082] A sample of *Aeropyrum pernix* was obtained from the Japan Collection of Microorganisms. *Aeropyrum pernix* cultures were grown in a solution of autoclaved sea water supplemented with bactoyeast extract, trypticase peptone and sodium thiosulphate for three days in an oil bath maintained at 95°C.

[0083] *Aeropyrum pernix* genomic DNA was collected by standard procedures. The gene coding for KvAP starting from methionine 14 was cloned by polymerase chain reaction (PCR) amplification of the genomic DNA and inserted into the protein expression vector pQE60 (Qiagen) between NcoI and BglII restriction endonuclease sites with a thrombin cleavage site between a carboxy-terminal hexahistidine sequence and the channel.

[0084] Channel protein was expressed in XL1-blue cell cultures grown in LB medium supplemented with 10mM BaCl₂ on induction with 0.4mM isopropyl-b-D-thiogalactopyranoside (IPTG). Expressed protein was extracted with 40mM decylmaltoside (DM) and purified on a Talon Co²⁺ affinity column (Clontech).

[0085] The protein was maintained in 5mM DM, 20mM Tris, pH 8.0, and 100mM KCl. Nonspecifically bound protein was washed using 15mM imidazole added to the above buffer, and the channel then eluted with 400mM imidazole. Immediately after elution, 1.0 unit of thrombin (Roche) per 3.0 mg channel was added to cleave the hexahistidine sequence overnight at room temperature. Protein was concentrated to about 15 mg ml⁻¹ and run on a Superdex-200 (10/30) column (Pharmacia) in the above buffer.

[0086] MALDI-TOF mass spectrometry (PerSeptive Biosystems Voyager-STR) and N-terminal sequencing analysis (Rockefeller University Protein/DNA Technology Center) indicated that the KvAP protein undergoes a modification during expression in which the first five residues of the encoded construct are replaced with a single leucine residue in the expressed channel protein.

Example 2: KvAP of Prokaryotic Organism, *Aeropyrum pernix*, is Functionally Similar to Eukaryotic Kv Channels.

[0087] KvAP channels were expressed in *Escherichia coli*, extracted with decylmaltoside, purified and reconstituted into planar lipid bilayers of 1-palmitoyl-2-oleoyl-phosphatidylglycerol (POPG) and 1-palmitoyl-2-oleoyl-phosphatidylethanolamine (POPE) for functional studies.

[0088] KvAP channels have a large conductance—the slope of the single-channel current-voltage relationship recorded in solutions containing 150 mM KCl and 10 mM HEPES, pH 7.0, on both sides of the membrane shows a conductance of approximately 170 pS. The presence of the K⁺ channel signature sequence indicates that the KvAP pore should be strongly selective for K⁺ versus Na⁺ ions.

[0089] To examine ion selectivity, the reversal potential of macroscopic tail currents in a tenfold K⁺ gradient by substituting 135mM NaCl for 135mM KCl in the solution on one side of the membrane. The measured reversal potential is -56.5 ± 1.2 mV, which is near the Nernst potential for a perfectly K⁺ selective pore at room temperature (21°C).

Example 3: KvAP of Prokaryotic Organism, *Aeropyrum pernix*, is Structurally Similar to Eukaryotic Kv Channels.

[0090] To examine the structural similarity of KvAP to eukaryotic K⁺ channel pores, the ability of a small protein toxin from scorpion venom to inhibit the KvAP channel was examined.

[0091] Venomous animals, such as scorpions, exploit the conservation of ion-channel structure by producing a toxin that recognizes a structural feature common to an entire family of ion channels. By making many sequence variants of the same basic toxin structure, a scorpion can inhibit virtually every member of an ion channel family. The scorpion *Leiurus quinquestriatus hebraeus* specializes in a family of pore-blocking toxins, exemplified by charybdotoxin (CTX), which fit, like a key to a lock, to the pore entryway of K⁺ channels.

[0092] CTX inhibits the KvAP channel with a dissociation constant (K_d) of about 0.4 mM. We emphasize that CTX would not bind to the KvAP channel if its pore were not very similar in structure to that of eukaryotic K⁺ channels.

Example 4: Voltage-Dependence of KvAP is Similar to Eukaryotic Kv Channels.

[0093] To determine the orientation of channels incorporated into planar lipid bilayers, we used CTX, which causes inhibition by binding only to the extracellular side. KvAP channels open in response to membrane depolarization (e.g., when the voltage of the CTX-insensitive (intracellular) side of the membrane is made positive relative to the CTX-sensitive (extracellular) side. KvAP channels are strongly voltage-dependent, opening as a function of membrane voltage, similar to *Shaker* and other eukaryotic neuronal Kv channels.

Example 5: Isolation of KvAP Voltage Sensor (S1-S4).

[0094] DNA for the isolated voltage sensor (from KvAP) encoding Met1 to Lys147 was cloned into a pQE60 expression vector (Qiagen) between *Nco*I and *Bgl*II sites with a thrombin cleavage site followed by a C-terminal hexahistidine sequence.

[0095] Protein was expressed in *E. coli* XL1-Blue cells by induction (at A₆₀₀ ~ 1.0) with 0.4 mM isopropyl-β-D-thiogalactopyranoside (IPTG) for 4 hours at 37°C. Cells were harvested and lysed in 50 mM Tris, pH 8.0, 100 mM KCl, containing 1 μg ml⁻¹ Leupeptin, 1 μg ml⁻¹ Pepstatin, 2 μg ml⁻¹ Aprotinin and 1 mM PMSF (Sigma) to inhibit proteases.

[0096] Protein was then extracted from the cell lysate for 3 hours at room temperature in the above solution by adding 40 mM decylmaltoside (DM). The extracted cell lysate was centrifuged at 16,000 rpm for 20 minutes and the supernatant was collected and loaded onto a Talon Co²⁺ affinity column (Clontech) equilibrated in 5mM DM, 20 mM Tris, pH 8.0, and 100 mM KCl. Nonspecifically bound protein was washed using 10 mM imidazole added to the above buffer, and the voltage sensor domain was eluted with 300 to 400 mM imidazole in the above buffer. The isolated voltage sensor domain was then dialyzed against 100 ml of the above buffer for ~ 7-8 hours and transferred to 100 ml of fresh buffer for dialysis overnight. Voltage sensor domain was concentrated to ~ 5 mg ml⁻¹, calculated by 280 nm absorbance using the extinction coefficient $\epsilon = 1.01 \text{ (mg ml}^{-1} \cdot \text{cm)}^{-1}$ determined from amino acid analysis. Purification yields ~ 3 mg of voltage sensor domain protein per liter of bacterial culture.

[0097] Analysis by MALDI-TOF mass spectrometry (PerSeptive Biosystems Voyager-STR) and N-terminal sequencing indicated that the N-terminus undergoes modification during expression in which the first five residues of the encoded constructs are replaced with a single leucine residue.

Example 6: Isolated Voltage Sensor Domain Retains Native Structure and Isolates and Binds to Toxins.

[0098] Isolated voltage sensor was expressed and purified according to Example 5. To generate the voltage sensor domain column for isolation of toxins, 0.1 ml of Co²⁺ resin was washed with water and then equilibrated with Buffer A (20 mM Tris pH 8.0, 100 mM KCl, and 10mM DM) in an eppendorf tube by 3-4 rounds of centrifugation (500 rpm) to collect resin, careful removal of the supernatant with a pipette and resuspension of the resin in either 1 ml of water or 0.4 ml of Buffer A.

[0099] Approximately 2 mg of voltage sensor domain was added to the equilibrated resin. The resin and voltage sensor domain protein were incubated for ~ 15 minutes. The resin was then applied to a micro chromatography column (Biorad). Samples of the voltage sensor domain prior to addition to the resin and the flow through after addition of resin to the column

was kept and later run on an SDS gel to ensure that an excess of protein has been added to the resin and saturated with protein.

[00100] The column was washed twice with 2 column volumes of Buffer A to remove any remaining unbound voltage sensor domain protein. A control column was prepared containing 0.1 ml of resin treated equivalently with the exception that instead of adding voltage sensor domain protein to the equilibrated resin, the same volume of Buffer A was added.

[00101] Venom from *Grammostola spatulata* (SpiderPharm) was diluted ten fold in Buffer A and 0.1 ml of the venom stock was applied to the column with bound S1-S4 domain or the control column. Both columns were washed to minimize non-specifically bound toxins, first in 4 column volumes Buffer A and then 4 column volumes Buffer A with 10 mM imidazole.

[00102] Remaining protein was eluted from both columns with 0.1ml of Buffer A containing 400 mM imidazole and reduced with 50 mM DTT at 37°C for 2 hours to improve separation by reverse phase high performance liquid chromatography (HPLC). Equal volumes of eluted, reduced protein from the two columns were run on an Agilent 1100 Series HPLC with a C-18 reverse-phase 5µm 80Å column using a 2 min isocratic flow of 75 % mobile phase A (H₂O, 0.1 % TFA) and 25 % mobile phase B (90 % acetonitrile, 10 % H₂O, 0.1 % TFA) followed by a 25 % -55 % mobile phase B gradient over 40 minutes. Peaks are collected and analyzed by MALDI-TOF mass spectrometry focusing on the low molecular weight range (~800-10,000 Da).

[00103] The isolate voltage sensor immobilized to a resin in the column efficiently purifies toxins from tarantula venom (Figure 3A). These toxins also inhibit functional KvAP channels in an electrophysiological assay (Figure 3B).

[00104] Thus, the data show that the isolated voltage sensor retains native structure due to binding of protein toxins with high affinity to the voltage sensor.

[00105] These experiments were performed with voltage-dependent ion channels from *Aeropyrum pernix*. However, due to the close homology between the amino acid sequences of voltage-dependent ion channels across species, the present invention can be applied to voltage sensor domains from any species, including *Homo sapiens*.

What is claimed is:

1. A composition of matter suitable for use in identifying chemical compounds that bind to voltage-dependent ion channel proteins, the composition comprising a screening protein that comprises an ion channel voltage sensor domain of the ion channel protein immobilized on a solid support.
2. The composition of claim 1, wherein the ion channel protein is a potassium ion channel protein.
3. The composition of claim 1, wherein the ion channel protein is a sodium ion channel protein.
4. The composition of claim 1, wherein the ion channel protein is a calcium ion channel protein.
5. The composition of claim 1, wherein the ion channel protein is an *Aeropyrum pernix* ion channel protein.
6. The composition of claim 5, wherein the ion channel protein is KvAP.
7. The composition of claim 1, wherein the ion channel protein is a *Homo sapien* ion channel protein.
8. The composition of claim 1, wherein the five N-terminal residues of the screening protein are replaced by a single leucine residue.
9. The composition of claim 1, wherein the screening protein excludes an ion conduction pore.

10. The composition of claim 1, wherein the screening protein comprises an amino acid sequence consisting essentially of the voltage sensor.
11. The composition of claim 1, wherein the solid support is a resin.
12. The composition of claim 11, wherein the resin comprises cobalt.
13. The composition of claim 11, wherein the resin comprises nickel.
14. The composition of claim 13, wherein the nickel is nickel-NTA agarose.
15. The composition of claim 11, wherein the resin comprises glutathione sepharose.
16. A kit suitable for use in identifying chemical compounds that bind to voltage-dependent ion channel proteins, the kit comprising a screening protein that comprises an ion channel voltage sensor domain of the ion channel protein and a solid support.
17. The kit of claim 16, wherein the ion channel protein is a potassium ion channel protein.
18. The kit of claim 16, wherein the ion channel protein is a sodium ion channel protein.
19. The kit of claim 16, wherein the ion channel protein is a calcium ion channel protein.
20. The kit of claim 16, wherein the ion channel protein is an *Aeropyrum pernix* ion channel protein.
21. The kit of claim 20, wherein the ion channel protein is KvAP.

22. The kit of claim 16, wherein the ion channel protein is a *Homo sapien* ion channel protein.
23. The kit of claim 16, wherein the five N-terminal residues of the screening protein are replaced by a single leucine residue.
24. The kit of claim 16, wherein the screening protein excludes an ion conduction pore.
25. The kit of claim 16, wherein the screening protein comprises an amino acid sequence consisting essentially of the voltage sensor.
26. The kit of claim 16, wherein the solid support is a resin.
27. The kit of claim 26, wherein the resin comprises cobalt.
28. The kit of claim 26, wherein the resin comprises nickel.
29. The kit of claim 28, wherein the nickel is nickel-NTA agarose.
30. The kit of claim 26, wherein the resin comprises glutathione sepharose.
32. The kit of claim 16, further comprising one or both of a label and a buffer.
32. The kit of claim 31, wherein the screening protein is bound to the solid support.
33. The kit of claim 16, wherein the screening protein is labeled.
34. A labeled screening protein suitable for use in identifying chemical compounds that bind to a voltage-dependent ion channel protein, the labeled screening protein comprising an ion channel voltage sensor domain of the ion channel protein and a detectable label.

35. The labeled screening protein of claim 34, wherein the ion channel protein is a potassium ion channel protein.

36. The labeled screening protein of claim 34, wherein the ion channel protein is a sodium ion channel protein.

37. The labeled screening protein of claim 34, wherein the ion channel protein is a calcium ion channel protein.

38. The labeled screening protein of claim 34, wherein the ion channel protein is an *Aeropyrum pernix* ion channel protein.

39. The labeled screening protein of claim 38, wherein the ion channel protein is KvAP.

40. The labeled screening protein of claim 34, wherein the ion channel protein is a *Homo sapien* ion channel protein.

41. The labeled screening protein of claim 34, wherein the five N-terminal residues of the screening protein are replaced by a single leucine residue.

42. The labeled screening protein of claim 34, wherein the screening protein excludes an ion conduction pore.

43. The labeled screening protein of claim 34, wherein the screening protein comprises an amino acid sequence consisting essentially of the voltage sensor.

44. The labeled screening protein of claim 34, wherein the detectable label is radioactive.

45. The labeled screening protein of claim 34, wherein the detectable label is colorimetric.

46. A method for screening for drug candidates that target voltage dependent ion channel protein, the method comprising:

providing a screening protein;

contacting the screening protein with a chemical compound;

determining whether the chemical compound binds to the screening protein;

wherein chemical compounds that bind to the screening protein are drug candidates.

47. A method according to claim 46, wherein the screening protein is immobilized on a solid support.

48. A method according to claim 46, wherein the chemical compound is immobilized on a solid support.

49. A method according to claim 46, wherein the chemical compound is a biological molecule.

50. A method according to claim 49, wherein the biological molecule is a polyamino acid.

51. A method according to claim 46, wherein the chemical compound is a small molecule.

52. A method according to claim 46, wherein the drug candidate alters the target voltage dependent ion channel proteins.

53. A method according to claim 46, wherein the drug candidate is a candidate for a drug useful for treating a condition mediated by aberrant electrical activity.

54. A method according to claim 53, wherein the aberrant electrical activity initiates uptake or release of neurotransmitters.

55. A method according to claim 53, wherein the aberrant electrical activity initiates contraction of muscles.

56. A method according to claim 46, wherein the drug candidate is a candidate for a drug for treating epilepsy.

57. A method according to claim 46, wherein the drug candidate is a candidate for a drug for treating arrhythmia.

58. A method according to claim 46, wherein the drug candidate is further tested for activity against a condition mediated by aberrant electrical activity.

59. A method according to claim 58, wherein the aberrant electrical activity initiates uptake or release of neurotransmitters.

60. A method according to claim 58, the aberrant electrical activity initiates contraction of muscles.

61. A method according to claim 46, wherein the drug candidate is further tested for activity against epilepsy.

62. A method according to claim 46, wherein the drug candidate is further tested for activity against arrhythmia.

Figure 2B

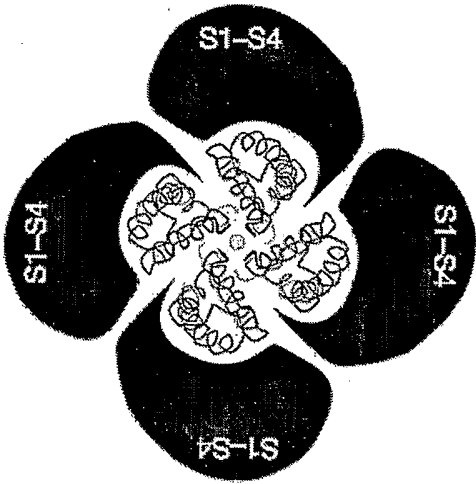


Figure 2A

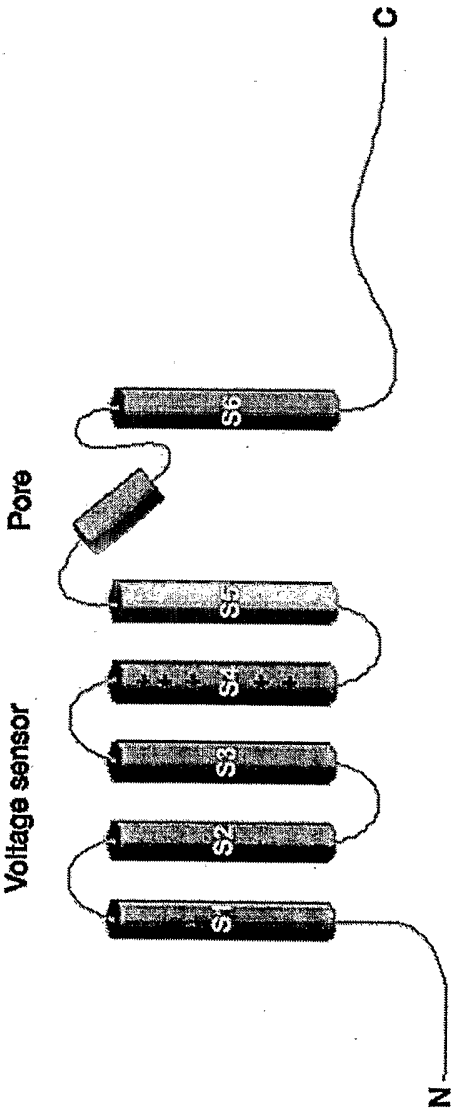


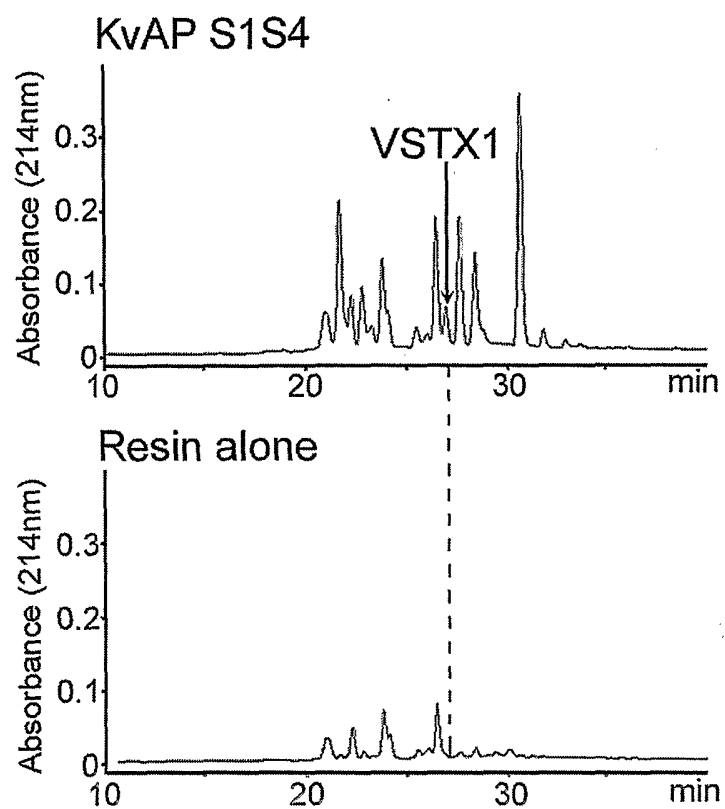
Figure 3**a**

Figure 3B

