ICA-105574 Interacts with a Common Binding Site to Elicit Opposite Effects on Inactivation Gating of EAG and ERG Potassium Channels

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ABSTRACT

Rapid and voltage-dependent inactivation greatly attenuates outward currents in ether-a-go-go-related gene (ERG) K⁺ channels. In contrast, inactivation of related ether-a-go-go (EAG) K⁺ channels is very slow and minimally reduces outward currents. ICA-105574 (ICA, or 3-nitro-N-[4-phenoxyphenyl]-benzamide) has opposite effects on inactivation of these two channel types. Although ICA greatly attenuates ERG inactivation by shifting its voltage dependence to more positive potentials, it enhances the rate and extent of EAG inactivation without altering its voltage dependence. Here, we investigate whether the inverse functional response to ICA in EAG and ERG channels is related to differences in ICA binding site or to intrinsic mechanisms of inactivation. Molecular modeling coupled with site-directed mutagenesis suggests that ICA binds in a channel-specific orientation to a hydrophobic pocket bounded by the S5/pore helix/S6 of one subunit and S6 of an adjacent subunit. ICA is a mixed agonist of mutant EAG and EAG/ERG chimera channels that inactivate by a combination of slow and fast mechanisms. With the exception of three residues, the specific amino acids that form the putative binding pocket for ICA in ERG are conserved in EAG. Mutations introduced into EAG to replicate the ICA binding site in ERG did not alter the functional response to ICA. Together these findings suggest that ICA binds to the same site in EAG and ERG channels to elicit opposite functional effects. The resultant agonist or antagonist activity is determined solely by channel-specific differences in the mechanisms of inactivation gating.

Introduction

Ether-a-go-go (EAG) K⁺ channels, first described in Dro sophila (Warnke et al., 1991), are highly expressed in the mammalian central nervous system (Ludwig et al., 1994; Martin et al., 2008) and a variety of tumors (Hammerlein et al., 2006; Mello de Queiroz et al., 2006; Paro et al., 1999). EAG channels activate rapidly and exhibit only a very subtle and slow form of inactivation (Garg et al., 2012). The related ether-a-go-go-related gene (ERG) K⁺ channel was discovered by screening of a human hippocampus cDNA library (Warnke and Gazetzky, 1994), and functional analysis revealed that it activates more slowly than does EAG and undergoes a very rapid inactivation that greatly reduces channel open probability at positive potentials (Smith et al., 1996; Spector et al., 1996). Both slow (EAG) and fast (ERG) inactivation are modulated by voltage and voltage dependence. Here we investigate whether the inverse functional response to ICA in EAG and ERG channels is related to differences in ICA binding site or to intrinsic mechanisms of inactivation.

ICA-105574 (ICA, or 3-nitro-N-[4-phenoxyphenyl]-benzamide) is a mixed agonist of mutant EAG and EAG/ERG chimera channels that inactivate by a combination of slow and fast mechanisms. With the exception of three residues, the specific amino acids that form the putative binding pocket for ICA in ERG are conserved in EAG. Mutations introduced into EAG to replicate the ICA binding site in ERG did not alter the functional response to ICA. Together these findings suggest that ICA binds to the same site in EAG and ERG channels to elicit opposite functional effects. The resultant agonist or antagonist activity is determined solely by channel-specific differences in the mechanisms of inactivation gating.

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ABBR eviations: bEAG1, bovine ether-a-go-go type 1; hEAG1, human ether-a-go-go type 1; hERG1, human ether-a-go-go-related gene type 1; ICA, 3-nitro-N-[4-phenoxyphenyl]-benzamide (ICA-105574); \( i_{\text{end}} \), current at the end of the pulse; \( i_{\text{Kc}} \), rapid delayed rectifier K⁺ current; \( i_{\text{peak}} \), peak outward current; MD, molecular dynamics; WT, wild type.
3-Nitro-N-(4-phenoxophenyl)-benzamide (ICA-105574, or ICA) is a recently discovered compound that shortens the duration of cardiac action potentials by inducing a dramatic shift (e.g., +183 mV at 2 μM) in the voltage dependence of hERG1 inactivation to more positive potentials (Gerlach et al., 2010). In striking contrast to its inhibition of hERG1 channel inactivation, we recently reported that ICA enhances inactivation of human EAG1 (hEAG1, Kv10.1) channels (Garg et al., 2012). In addition to differences in their response to ICA, inactivation of hERG1, but not hEAG1, is slowed by external tetraethylammonium and elevated [K+]o (Garg et al., 2012). Despite these differences, the selectivity filter appears needed.

Materials and Methods

Molecular Biology. Human EAG1 (KCNH1; National Center for Biological Technology Information Reference Sequence: NM_000238.3) cDNA cloned into psGEMHE oocyte expression vector was kindly provided by the late Dr. Dennis Wray. HERG1 (KCNH2, isof orm 1a, National Center for Biological Technology Information Reference Sequence: NM_000238.2), was cloned into the psP64 oocyte expression vector. Mutations in wild-type (WT) hEAG1 cDNA were made using the QuickChange site-directed mutagenesis kit (Agilent Technologies, Santa Clara, CA) and were verified by DNA sequence analyses. Plasmids were linearized using NotI (psGEMHE) or EcoR1 (psP64). HEG1 cRNA was in vitro transcribed with the mMessage Machine T7 kit (Life Technologies, Grand Island, NY). cRNA was transcribed with the mMessage Machine SP6 kit (Ambion, Austin, TX). cRNA was quantified using RiboGreen assay (Life Technologies).

Two-Electrode Voltage Clamp of Xenopus Oocytes. Procedures for harvesting oocytes from Xenopus laevis were as described elsewhere (Garg et al., 2012) and were approved by the University of Utah Institutional Animal Care and Use Committee. The isolation, culture, and injection of oocytes with cRNA were performed as described previously (Goldin, 1991; Stühmer, 1992). Injected oocytes were incubated for 1–5 days at 18°C in Barth’s saline solution before use in voltage clamp experiments. Currents were recorded from oocytes with use of a standard two-microelectrode voltage clamp technique (Goldin, 1991; Stühmer, 1992) and agarose-cushion microelectrodes. 

Solutions. Barth’s solution contained 88 mM NaCl, 2 mM KCl, 0.41 mM CaCl2, 0.33 mM Ca(NO3)2, 1 mM MgSO4, 2.4 mM NaHCO3, 10 mM HEPES, 1 mM pyruvate, and 50 mg/l gentamycin; pH was adjusted to 7.4 with NaOH. KCM211 solution contained 98 mM NaCl, 2 mM KCl, 1 mM CaCl2, 1 mM MgCl2, and 5 mM HEPES; pH was adjusted to 7.6 with NaOH. ICA was purchased from Sigma-Aldrich (St. Louis, MO) and AKos GmbH (Steinen, Germany) and prepared as a 10 mM stock solution in dimethyl sulfoxide. Final ICA was obtained by dilution of the stock solution with KCM211 immediately before use for each experiment. TEA was purchased from Sigma-Aldrich.

Data Analysis. Digitized data were analyzed off-line with pCLAMP9 (Molecular Devices). Origin 8 (OriginLab, Redmond, WA) software. The concentration-effect relationship for ICA inhibition of hEAG current measured at +30 mV was fitted with a Hill equation. ICA enhanced currents at low concentrations and reduced currents at high concentrations of some mutant channels. For these mutant channels, an effective IC50 (Table 1) was determined simply by noting the concentration that reduced control current by 50%. All data are expressed as mean ± S.E.M. (n = number of oocytes) and evaluated by an unpaired Student’s t test where appropriate (P ≤ 0.05 was considered to be a statistically significant difference).

Molecular Modeling. Homology models of the closed and open channel conformations were generated using Modeller99v9 with the KcsA crystal structure (PDB 2HVK) as a template for the closed state model and the KvAP (1ORQ) and the high resolution Mthk (PDB 3LDC) crystal structures as templates for the open conformation. Modeling details were described previously (Stary et al., 2010). All mutant hEAG1 channels (F359L, M431F, M458L, L463M) were generated in Pymol. Molecular Dynamic (MD) simulations of open and closed models were performed using Gromacs, version 4.5.4 (Hess et al., 2008). WT and mutant channels were embedded in an equilibrated simulation box consisting of 280 dioleoylphosphatidylcholine lipids. Lipid parameters were taken from Siu et al. (Siu et al., 2008), and the TIP3P water model was used (Jorgensen et al., 1983). The amber99sb force field (Hornak et al., 2006) was used for the protein. Electrostatic interactions were calculated explicitly at a distance < 1 nm and long-range electrostatic interactions were calculated at every > 1 nm by particle-mesh Ewald summation (Darden et al., 1993). Lennard-Jones interactions were calculated with a cutoff of 1 nm. All bonds were

Table 1

<table>
<thead>
<tr>
<th>Mutation in hEAG1</th>
<th>Mean IC50 for ICA ± S.E.M.</th>
<th>Fold increase or decrease (△) in IC50</th>
<th>n</th>
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<tr>
<td>(WT)</td>
<td>0.44 ± 0.03</td>
<td>5</td>
<td>△</td>
</tr>
<tr>
<td>V356A**</td>
<td>0.08 ± 0.009</td>
<td>3</td>
<td>5.5</td>
</tr>
<tr>
<td>V356E**</td>
<td>28.8 ± 2.6</td>
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<td>65</td>
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<tr>
<td>F359A*</td>
<td>29.6 ± 9.0</td>
<td>3</td>
<td>67</td>
</tr>
<tr>
<td>F359L</td>
<td>&gt;30</td>
<td>4</td>
<td>&gt;68</td>
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<tr>
<td>L427A**</td>
<td>0.17 ± 0.01</td>
<td>3</td>
<td>2.6</td>
</tr>
<tr>
<td>M431A</td>
<td>1.9 ± 0.34</td>
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<td>4.3</td>
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<td>L434A**</td>
<td>8.5 ± 0.06</td>
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<td>19</td>
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<tr>
<td>L434C**</td>
<td>4.8 ± 0.2</td>
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<td>11</td>
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<tr>
<td>M457A</td>
<td>&gt;30</td>
<td>4</td>
<td>&gt;68</td>
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<td>20.2 ± 1.2*</td>
<td>4</td>
<td>46</td>
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<tr>
<td>M458E**</td>
<td>0.45 ± 0.08</td>
<td>3</td>
<td>no change</td>
</tr>
<tr>
<td>L462A**</td>
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<td>3</td>
<td>8.6</td>
</tr>
<tr>
<td>L463A**</td>
<td>41.2 ± 8.2*</td>
<td>3</td>
<td>94</td>
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<td>Y464A**</td>
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<td>6.3</td>
</tr>
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<td>I467A**</td>
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<td>2.5</td>
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<td>F468A**</td>
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<tr>
<td>F468A**</td>
<td>3.1 ± 0.48</td>
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hEAG1, human ether-a-go-go type 1; ICA, -nitro-N-(4-phenoxophenyl)-benzamide (ICA-105574); WT, wild-type.

* NS, nonsignificant (P > 0.05).

** Effective IC50.

△ P < 0.01.

** P < 0.001 compared with WT.
ICA Binds to the Pore Domain of hERG1 and hEAG1 Channels to Exert Opposite Effects on Inactivation.

The results of ICA on WT hERG1 and hEAG1 channels expressed in *Xenopus* oocytes are shown in Fig. 1. Channels were activated with a 10-second pulse to +30 mV from a holding potential of −100 mV. As reported previously (Gerlach et al., 2010; Garg et al., 2011, 2012), ICA caused a marked and concentration-dependent enhancement of hERG1 current (Fig. 1A), but inhibited hEAG1 current (Fig. 1B) by reducing both the initial peak outward current (*I*<sub>peak</sub>) and inducing a time-dependent decay of current during the pulse. Inhibition of hEAG1 current by ICA is caused by an enhancement of intrinsic inactivation and is not attributable to open channel block (Garg et al., 2012). The inhibitory effect of ICA on hEAG1 was more potent than was the activation effect on hERG1 channels. The IC<sub>50</sub> for ICA inhibition of hEAG1 was 1.38 ± 0.04 μM for *I*<sub>peak</sub>, and 0.44 ± 0.03 μM for current at the end of the pulse, *I*<sub>end</sub> (n = 5) (Fig. 1C).

Using scanning mutagenesis and functional analysis of mutant hERG1 channels, we recently proposed that ICA binds to a hydrophobic pocket formed by the S5/pore helix/S6 of one subunit and S6 segment of an adjacent channel subunit.

**Fig. 1.** The pore domain of EAG1 and ERG1 channels determines functional response to ICA. (A) ICA activates WT hERG1 channel current. (B) ICA inhibits WT hEAG1 channel current. For traces shown in A and B, currents were activated with 10-second pulses to +30 mV from a holding potential of −100 mV. (C) ([ICA]-response relationship for inhibition of hEAG1 channel currents (n = 5). ICA inhibited *I*<sub>peak</sub>, peak outward current (IC<sub>50</sub> = 1.38 ± 0.04 μM; *n*<sub>5</sub> = 1.4). (D–I) Effect of ICA on EAG1/ERG1 chimera channels. In each panel, the diagram indicates regions of subunits contributed by bEAG1 (black) and hERG1 (gray). Currents were elicited with 10-second pulses to +30 mV from a holding potential of −100 mV. The fold-change in *I*<sub>end</sub> induced by ICA for each chimera channel was as follows: (D) EAG/ERG<sub>S45L-S6</sub> (1.9 ± 0.03 at 10 μM; 3.6 ± 0.6 at 30 μM, n = 3). (E) ERG/EAG<sub>S45L-S6</sub> (0.58 ± 0.07 at 1 μM; 0.24 ± 0.04 at 3 μM, n = 4). (F) ERG/EAG<sub>S6</sub> (9.6 ± 3.5 at 10 μM; 41 ± 11 at 30 μM, n = 4). (G) ERG/EAG<sub>ERGturret</sub> (15 ± 1.9 at 10 μM; 26 ± 3 at 30 μM, n = 3). (H) ERG/EAG<sub>S45L-S6</sub> (9.7 ± 1.6 at 10 μM; 6.1 ± 1.0 at 30 μM, n = 3). (I) ERG/EAG<sub>ERGturret-pore</sub> selectivity filter (% change in *I*<sub>end</sub> = 9 ± 3 at 3 μM; 4 ± 2 at 10 μM; −3 ± 3 at 30 μM, n = 3).
To identify the region of the EAG1 channel responsible for the inhibitory effect of ICA, we first used an unbiased approach and examined several previously characterized chimera channels (Ficker et al., 1998) constructed from bovine EAG1 (bEAG1) and hERG1. The amino acid sequences of bovine and human EAG1 are 97% identical for the entire proteins and 100% identical in the S1–S6 regions. First, the role of the pore module was investigated. ICA was an agonist when the pore region (S45 linker-S6) of the chimera channel was contributed by hERG1 (Fig. 1D), but was an antagonist when the same pore region was supplied by bEAG1 (Fig. 1E). Next, ICA was tested on chimeras in which only a limited region of the pore domain of hERG1 was replaced by their bEAG1 counterpart. When only the S6 segment (Fig. 1F) or the turret (Fig. 1G) was supplied by bEAG1, ICA acted as an agonist. Finally, when the S45 linker-S5 (Fig. 1H) or the turret-pore helix-selectivity filter (Fig. 1I) was supplied by bEAG1, the effects of ICA were biphasic; 30 μM ICA induced or enhanced the rate of slow inactivation and caused a smaller increase in current, compared with 10 μM ICA. Together, the findings obtained with hERG1/bEAG1 chimeras indicate that the pore domain (S5–S6) region determines the channel-specific response to ICA.

ICA Is a Mixed Agonist of a Fast-Inactivating Mutant hEAG1 Channel. Two Ser residues, located on either side of the selectivity filter, are key determinants of fast P/C-type inactivation in hERG1 (Suessbrich et al., 1997). In bEAG1 channels, combined mutation of the residues located in the homologous position as these two Serines induces fast inactivation (Ficker et al., 1998). Introduction of the same two homologous position as these two Serines induces fast inactivation in hERG1 (Suessbrich et al., 1997). In bEAG1, the effects of ICA were biphasic; 30 μM ICA induced or enhanced the rate of slow inactivation and caused a smaller increase in current, compared with 10 μM ICA. Together, the findings obtained with hERG1/bEAG1 chimeras indicate that the pore domain (S5–S6) region determines the channel-specific response to ICA.

Molecular Determinants of ICA Interaction with hEAG1 Channels. Simulated docking of ICA to molecular models of the hEAG1 pore module was performed, and the findings were compared with those from our previous model of ICA bound to the hERG1 channel. Homology models of hEAG1 were constructed using the KvAP and MthK crystal structures (Jiang et al., 2003; Ye et al., 2010) as template for the open state and the KcsA crystal structure (Doyle et al., 1998) as template for the closed state. In hERG1, ICA was predicted to be oriented perpendicular to the axis of the S5 and S6 segments in both the closed and the open state dockings, with the nitro group facing toward the pore (Garg et al., 2011). For hEAG1, ICA also favored a perpendicular orientation in the open state, but the nitro group faces away from the pore and toward the lipids that surround the pore. ICA is unaffected by tetraethylammonium or changes in [K+]o (Garg et al., 2012). When activated by a 0.4-second pulse to +30 mV, 3 μM ICA reduced Ipeak and the inactivating component of outward T432S/A443S hEAG1 current, but doubled the magnitude of Iend (Fig. 2A). At 30 μM, ICA eliminated fast inactivation (Fig. 2A). ICA (1–30 μM) reduced Ipeak in a concentration-dependent manner (Fig. 2B), but exhibited a biphasic (mixed agonist) effect on Iend and reduced rectification of the Iend–V relationship (Fig. 2C). At 30 μM, ICA inhibited Ipeak (all potentials) and Iend (at test potentials < +10 mV). The [ICA]-response relationship for Ipeak and Iend at a single voltage (+30 mV) for T432S/A443S hEAG1 channels is compared with WT channels in Fig. 2D. Together, these findings suggest that the multiple effects of ICA on T432S/A443S hEAG1 channels represent the sum of two opposing actions: reduced fast (ERG1-like) inactivation to increase current plus inhibition, perhaps mediated by open channel block to reduce current. We next explore whether the opposite effects of ICA on fast versus slow modes of inactivation gating are mediated by ICA binding to the same or distinct sites in hERG1 and hEAG1 channels.
module (Fig. 3, A–C). In the closed state of hEAG1, ICA is orientated parallel to S5 and S6 (Fig. 3, D–F). Simulated docking of ICA to the open states of hERG1 and hEAG1 are compared in Supplemental Fig. 2. In hEAG1, ICA resides in a hydrophobic pocket formed by residues Met431, Leu434, Met458, Tyr464, Ile467, and Phe359. The location of this binding pocket is quite similar to that previously described for hERG1 (Garg et al., 2011). However, sequence differences between hERG1 and hEAG1 lead to different-shaped binding pockets for ICA (Supplemental Fig. 2, C and E). ICA protrudes deeply into the cleft between two adjacent subunits in the hERG1 channel (Supplemental Fig. 2A). By contrast, in hEAG1, Tyr464 forms a barrier at the S6-S6 interface, leading to a shallower binding mode for ICA (Fig. 3; Supplemental Fig. 2D). ICA does not form π-π stacking interactions with Tyr464 in either the closed or the open state of hEAG1 and, thus, might not be able to stabilize the phenyl group in the down conformation, as previously suggested for hERG1 (Garg et al., 2011). In addition, stabilizing hydrogen bonds predicted between ICA and selectivity filter residues in hERG1 are lacking in hEAG1.

Considering both open and closed hEAG1 model simulations, 11 residues are predicted to be in close proximity to ICA: Leu427, Met431, and Leu434 in the pore helix; Val356 and Phe359 in S5; Leu463, Tyr464, Ile467, and Phe468 in S6 of one subunit; and Met457 and Met458 in the S6 of an adjacent subunit. To corroborate the modeling results, we mutated to Ala each of these 11 residues. Seven of the 11 Ala substitutions reduced the sensitivity (increased IC50) of the mutant channel to ICA by 4-fold, compared with WT hEAG1 (Table 1; Supplemental Fig. 3). The I467A mutation increased the IC50 by 2.5-fold, whereas V356A, L427A, and Y464A mutations reduced IC50 by 2.5–6-fold. Val356, Leu427, and Ile467 are predicted to interact with ICA in the closed but not the open state. Because of the poor expression of L427A mutant channel (requiring 100 times more cRNA and longer incubation time in comparison with WT hEAG) and its location near the selectivity filter (P/C-type inactivation gate), Leu427 residue was not analyzed further. To explore the potential significance of Ile467 and Val356 to ICA binding, each was mutated to the more perturbing Glu. Accordingly, both V356E and I467E mutations increased the IC50 for ICA by >55-fold (Supplemental Fig. 3; Table 1). Thus, mutagenesis confirmed the importance of all the residues predicted by molecular modeling to interact with ICA in either the open or the closed state of the hEAG1 channel.

Some of the molecular determinants of ICA binding to hEAG1 align with those previously described for hERG1. For example, mutation of Phe557, Phe619, Leu622, and Phe656 in hERG1 reduced the sensitivity to the activator effect of ICA (Garg et al., 2011); similarly, mutation of the corresponding residues to Ala in hEAG1 (Phe359, Met431, Leu434, and Phe468) reduced the inhibitory action of ICA. However, many homologous mutations yielded incongruous findings for the two channels. First and of most importance, the Y652A hERG1 channel is nearly insensitive to activation by ICA (Garg et al., 2011), whereas the homologous Y464A hEAG1 channel is more sensitive to inhibition (more inactivated) by ICA (Garg et al., 2012). Second, although the mutations L463A and M458A decreased the sensitivity of hERG1 channels (IC50 increased by 94-fold and 46-fold, respectively; Table 1) and V356A enhanced sensitivity to ICA (Garg et al., 2011), the corresponding mutations in hEAG1 (M651A, L646A, and M554A) were previously reported to not alter the response to ICA (Garg et al., 2011). Third, F557L hERG1 channels are insensitive to ICA, whereas the corresponding F359L hEAG1 channel is activated by ICA (Garg et al., 2012). We investigated these notable differences by further examining three of these key residues in hEAG1: Met458 and Tyr464 in S6 and Phe359 in S5.

Simulated dockings predicted that both Met458 in hEAG1 and the homologous residue Leu646 in hERG1 are in close
proximity to ICA. Nonetheless, substitution of Leu646 to either Ala (Garg et al., 2011) or Glu (Supplemental Fig. 4) did not alter hERG1 channel sensitivity to ICA. As noted above, M458A mutation in hEAG1 reduced ICA sensitivity; however, similar to L646E in hERG1, M458E did not alter hEAG1 sensitivity to ICA (Supplemental Fig. 4; Table 1), presumably because the acidic side chain of Glu is repelled from the hydrophobic pocket and, thus, does not affect ICA binding. In hERG1, three specific point mutations, Y652A (S6), F557L (S5), and L434C (pore helix), rendered the channel insensitive to 30 μM ICA, consistent with molecular modeling predictions (Garg et al., 2011). The effect of multiple ICA concentrations on mutant channels harboring the homologous substitutions in hEAG1 (Y464A, F359L, L434C) were examined (Fig. 4, A–D). Consistent with Leu434 contributing to ICA binding, L434C hEAG1 was less inhibited by ICA (IC50 = 4.8 ± 0.2 μM), compared with WT channels (Fig. 4, A and D). As we reported previously, Y464A promotes and ICA accentuates prominent inactivation from an open state (Fig. 4, B and D), whereas F359L (Fig. 4 C) appears to promote and ICA reverses inactivation from closed states (Garg et al., 2012). Molecular modeling predicts that the F557L mutation in hERG1 excludes ICA from interaction with its hydrophobic binding pocket (Garg et al., 2011), consistent with its insensitivity to the drug. In contrast, molecular modeling predicts that the hydrophobic pocket in F359L hEAG1 channels can accommodate ICA (Supplemental Fig. 5), albeit in a different orientation, compared with the WT hEAG1 channel. Together, molecular modeling predictions and functional analysis of many mutant channels indicate that ICA modulates inactivation gating of both hEAG1 and hERG1 channels by interacting with the same hydrophobic pocket defined by the S5-pore helix-S6 region of one subunit and S6 of an adjacent subunit. We next sought to determine whether the functional effect of ICA could be reversed (i.e., switched from inhibitor to agonist) if the putative hydrophobic pocket of hEAG1 was modified by mutagenesis to mimic the pocket present in hERG1 channels.

Introducing Putative hERG1 Binding Pockets into hEAG1 Does Not Alter Response to ICA. The S5-pore helix-S6 regions of hERG1 and hEAG1 are composed of 79 residues, and protein sequence alignment (Fig. 5A) indicates several differences between the two channels, including 8 residues in S5, 5 residues in the pore helix, and 14 residues in S6. However, in the putative ICA binding pocket defined by docking simulations using the open state models of hERG1 (Garg et al., 2011) and hEAG1 (Fig. 3), only one residue in the pore helix and two residues in S6 differ between the two channels (Fig. 5A). Three amino acid substitutions were introduced into hEAG1 (M431F in the pore helix; M458L and L463M in S6) to match the corresponding residues in hERG1. The resulting triple-mutant (M431F/M458L/L463M) channel retained WT hEAG1 biophysical properties and response to ICA (Fig. 5B), including a similar IC50 value for inhibition of Iend (0.49 ± 0.15 μM, n = 3; Fig. 5C). Can the putative ICA binding site in hERG1 be adequately recapitulated in hEAG1 by just three amino acid substitutions? Molecular modeling suggests remarkable similar binding modes of the triple hEAG1 channel, compared with the WT hERG1 channel. Simulated docking predicts that ICA binds perpendicular to the axis of the S5 and S6 segments in both the closed and the open state, and the nitro group faces toward the pore (Fig. 6), similar to the orientation of ICA in hERG1 (Garg et al., 2011). Furthermore, mutations M431F/M458L/L463M render the shape of the binding site to be more hERG1-like, allowing the drug to protrude deeply into the cleft formed by the interface of two adjacent subunits. Together, these modeling and experimental findings support the notion that intrinsic differences in the mechanisms of slow versus fast inactivation gating, and not differences in the binding site, determines whether ICA is a channel antagonist (hEAG1) or agonist (hERG1).

Discussion

ICA Binds to a Common Site of EAG1 and ERG1 Channels to Exert Opposite Effects on Inactivation. ICA inhibits outward K+ hEAG1 channel currents by enhancing slow inactivation (i.e., it is an agonist of intrinsic slow inactivation gating). In contrast, ICA enhances outward hERG1 K+ channel currents by inhibiting inactivation (i.e., it is an antagonist of intrinsic fast inactivation gating). Despite the opposite functional response to ICA, analysis of chimera ERG/EAG channels and multiple mutant channels clearly establish that the compound binds to a similar region, in a hydrophobic cleft between two adjacent subunits of the pore module in both hERG1 and hEAG1. A recent MD simulation study of hERG1 proposed that the binding pocket for ICA is located between the pore helices of two adjacent subunits and that the selectivity filter adopts a collapsed conformation in the inactivated state, precluding entry of the compound into the pocket (Kopfer et al., 2012). However, this binding mode does not include interaction with residues in S5, including
responses to ICA. F359A channels were less sensitive to machinery of slow inactivation in hEAG1 channels. These findings suggest that ICA directly affects the molecular activated F359L channels are activated by ICA. Together, efficacy of ICA to induce inactivation, whereas highly inactivated or have a lower than normal single channel open currents are much smaller than WT channel currents, with equivalent amounts of cRNA, F359L hEAG1 channel activation of hEAG1 channels by ICA exhibits strong co-sites on each channel. Consistent with multiple binding sites, are homotetramers, there could be four identical ICA binding sites on each channel. Consistent with multiple binding sites, activation of hERG1 channels by ICA exhibits strong cooperativity, with a Hill coefficient of 3.3 estimated for the concentration-response relationship (Gerlach et al., 2010). Slow inactivation of hEAG1 channels is modulated by a drug-binding pocket engineered to mimic hERG1 channel. (A) Amino acid sequence alignment of S5 and pore helix (PH)/selectivity filter (SF)/S6 region of hEAG1 and hERG1. Nonconserved amino acids are underlined. Conserved residues (blue) and nonconserved residues (red) predicted to line the hydrophobic ICA binding pocket in hERG1 are highlighted. Residues colored green were predicted to contribute to ICA binding site in closed state of hERG1 (but not predicted to interact with hERG1 in closed or open state). (B) Concentration-dependent inhibition of M431F/M458L/L463M hEAG1 channel currents by ICA. Currents were elicited with 10-second pulses to +30 mV. (C) ICA-response relationships for $I_{\text{peak}}$ (solid curve) and $I_{\text{end}}$ (dashed curve) quantified as fold change in current measured at a test potential of +30 mV for M431F/M458L/L463M (data points, ■ and ○) and WT hEAG1 (curves only, replotted from Fig. 1C). The IC$_{50}$ was $0.49 \pm 0.15 \mu M$ for $I_{\text{end}}$ and $2.96 \pm 0.82 \mu M$ for $I_{\text{peak}}$ ($n = 4$).

F557, a residue that we find to be of particular importance in modification of channel gating by ICA. Because both channels are homotetramers, there could be four identical ICA binding sites on each channel. Consistent with multiple binding sites, activation of hERG1 channels by ICA exhibits strong cooperativity, with a Hill coefficient of 3.3 estimated for the concentration-response relationship (Gerlach et al., 2010).

Slow inactivation of hEAG1 channels is modulated by a proposed interaction among three residues in close proximity and located in the S5 (Phe359), pore helix (Leu434), and S6 (Tyr464) of each subunit (Garg et al., 2012). In WT channels, inactivation is very slow and barely detectable but is greatly enhanced by ICA or mutations of Tyr464. Y464A hEAG1 channels exhibit far greater intrinsic slow inactivation than do WT channels, and ICA accentuates this altered mode of gating. Inactivation of Y464A channels can be prevented (WT gating restored) by introducing a second mutation of either Leu434 or Phe359 (Garg et al., 2012). In contrast to Tyr464, multiple mutations of Leu434 or Phe359 do not alter the biophysical properties of hEAG1 (Garg et al., 2012), but do affect the response to ICA. F359A and L434A/C reduce the efficacy of ICA to induce inactivation, whereas highly inactivated F359L channels are activated by ICA. Together, these findings suggest that ICA directly affects the molecular machinery of slow inactivation in hEAG1 channels.

F359A and F359L hEAG1 channels exhibited altered responses to ICA. F359A channels were less sensitive to inhibition by ICA (67-fold increase in IC$_{50}$), indicating a reduced binding affinity. In addition, ICA reduced F359A channel currents without inducing the prominent time-dependent decay of current during a depolarizing pulse seen with WT channels. We interpret this later effect to indicate that ICA enhances closed (but not open) state inactivation of F359A channels. Inhibition of F359A channels could also result from open channel block; however, we have previously presented extensive evidence that ICA induces both closed and open state inactivation of WT hEAG1 channels with no evidence of open channel block (Garg et al., 2012). On the basis of our molecular modeling results, ICA binds similarly to the open state of WT and F359L hEAG1 channels (Supplemental Fig. 2, D and E, WT; Supplemental Fig. 5, A and B, F359L). However, unlike WT channels, the activation of F359L channels was biphasic: currents were activated at all concentrations examined (1–30 μM) and peaked at 3 μM. ICA concentrations >3 μM led to progressively less activation that was accompanied by progressively more extensive time-dependent decay of outward currents (indicative of enhanced open channel inactivation). On the basis of injection of oocytes with equivalent amounts of cRNA, F359L hEAG1 channel currents are much smaller than WT channel currents, suggesting that these mutant channels are either highly inactivated or have a lower than normal single channel open probability. As discussed previously (Garg et al., 2012), we propose that ICA-mediated increase in F359L channel currents may be caused by a reduced rate of closed to inactivated state transitions.

Modification of channel gating has also been proposed as the mechanism responsible for activation of KCNQ2-5 (Kv7.2-Kv7.5) channels by retigabine, an anticonvulsant drug that shifts the voltage dependence of activation to more negative potentials. The putative binding site for retigabine is a hydrophobic binding pocket (Schenzer et al., 2005; Wuttke
et al., 2005; Lange et al., 2009) located in the same region described here for ICA binding to ERG and EAG channels. The primary molecular determinants of retigabine binding in KCNQ3 are Thr265 (S5), Leu314 (pore helix), and Leu338 (S6), homologous to key components of the ICA binding site in hEAG1 (Phe359, Leu434, Met458) and hERG1 (Phe557, Leu622, Leu646). Moreover, mutation of the aromatic residue in S5 to Leu renders hERG (F557L) channels as insensitive to retigabine. The homologous mutation in hEAG1 (F359L) reversed the effect of the ICA from antagonist to agonist activity, and the reverse mutation at the corresponding residue in KCNQ1 (L266W) leads to inhibition in a channel that is normally insensitive to retigabine (Schenzer et al., 2005). Another interesting analogy between EAG and KCNQ (specifically, KCNQ1) channels is that, in both, a tripartite mode of inactivation gating has been proposed, involving specific residues in the S5, pore helix, and S6 (Seebohm et al., 2005; Garg et al., 2012). Thus, gating of the selectivity filter in multiple, unrelated Kv channels is modulated by binding of lipophilic compounds to the hydrophobic cleft situated between two adjacent subunits in the pore module.

Clinical Relevance. Treatments for congenital and acquired long QT syndrome are limited. The recent discovery of several compounds that activate hERG1 channels initiates a promising pathway toward development of genotype-specific therapy for this life-threatening disorder. As a consequence of its profound inhibition of inactivation, ICA increases the magnitude of outward hERG1 currents more than has been observed for other activators, such as RPR260243 (Kang et al., 2006). Activation of human ether-a-go-go-related gene potassium channels by the dihydropyridine 1,3-bis(2-hydroxy-5-trifuoromethyl-phenyl)-urea (NS1643). Mol Pharmacol 69:266–277.


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ICA-105574 interacts with a common binding site to elicit opposite effects on inactivation gating of EAG and ERG potassium channels
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Supplemental Fig. 1. Elevated [K\textsuperscript{+}]\textsubscript{e} and extracellular tetraethylammonium (TEA, 10 mM) slow the rate of T432S/A443S hEAG1 inactivation. (A) Current elicited with a voltage step to +30 mV from a holding potential of ~60 mV in the presence of extracellular solution that contained either 2 mM or 10 mM [K\textsuperscript{+}]\textsubscript{e}. Dashed curve represents current measured with 2 mM K\textsuperscript{+} scaled to match peak of current measured with 10 mM K\textsuperscript{+}. (B) Effect of 10 mM TEA on current from same oocyte shown in panel A. Dashed curve represents current measured with 10 mM TEA scaled to match peak of current measured under control conditions (2 mM K\textsuperscript{+}, no TEA). (C) Normalized I\textsubscript{peak}-V relationships for T432S/A443S hEAG1 channels recorded under control conditions (2 mM K\textsuperscript{+}), and in the presence of elevated [K\textsuperscript{+}]\textsubscript{e} (10 mM K\textsuperscript{+}) and 10 mM TEA in the external solution (n = 7). (D) Comparison of inactivation time constant (τ) at +30 mV in the presence of 2 mM [K\textsuperscript{+}]\textsubscript{e}, 10 mM [K\textsuperscript{+}]\textsubscript{e} and 10 mM TEA (n = 7).
Supplemental Fig. 2. Comparison of simulated ICA dockings to homology models of hERG1 and hEAG1 pore modules in the open state. A, hERG1 pore module with ICA viewed from extracellular space. B, Side-view of ICA docked between two adjacent hERG1 subunits with interacting residues labeled. C, Map of ICA binding pocket located between two adjacent subunits of hERG1. D, hEAG1 pore module with ICA viewed from extracellular space. E, Side-view of ICA docked between two adjacent hEAG1 subunits with interacting residues labeled. F, Map of ICA binding pocket located between two adjacent subunits of hEAG1.
Supplemental Fig. 3. Effect of ICA on mutant hEAG1 channels. A – L, The 11 residues predicted by modeling to be in close proximity to ICA in either the open and closed state were mutated as indicated and the effect of ICA at the indicated concentrations on currents was measured. In each panel upper traces show currents measured during 10-s pulses to +30 mV. The [ICA]-response relationship for each mutant channel is plotted below each set of current traces. Leu427A, Met431 and Leu434 are located in the pore helix. Val356 and Phe359 are located in S5. Leu463, Ile467, Phe468 are located in S6 of one subunit, and Met457, Met458 and Leu462 are located in the S6 of an adjacent subunit (see Fig. 3).
Supplemental Fig. 4. Effect of ICA on L646E hERG1 and M458E hEAG1 channel currents. A and B, Currents were elicited with 1-s pulses to test potentials applied in 10-mV increments from −80 to +60 mV. Tail currents were measured at −70 mV. C, $I_{\text{peak}}-V$ relationships measured before (control) and in presence of 30 μM ICA ($n = 4$). Currents were normalized relative to the peak outward control current at +20 mV. D, Concentration-dependent inhibition of M458E hEAG1 channel currents by ICA. Currents were elicited with 10-s pulses to +30 mV. E, [ICA]-response (normalized $I_{\text{end}}$) relationships for M458E hEAG1 channels (IC$_{50} = 0.45 \pm 0.08$ μM; $n = 3$).
Supplemental Fig. 5. Molecular models of ICA docked to F359L hEAG1 channel. A and B, Extracellular view (A), and side-view of two adjacent subunits (B) with ICA bound to the open state of the F359L hEAG1 pore module. C and D, Similar views of ICA docking to closed state model.