Ethanol Activation of Protein Kinase A Regulates GABA_{A} \alpha1 Receptor Function and Trafficking in Cultured Cerebral Cortical Neurons

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Received November 19, 2012; accepted February 12, 2013

ABSTRACT

Ethanol exposure produces alterations in GABAergic signaling that are associated with dependence and withdrawal. Previously, we demonstrated that ethanol-induced protein kinase C (PKC) \gamma signaling selectively contributes to changes in GABA_{A} \alpha1 synaptic receptor activity and surface expression. Here, we demonstrate that protein kinase A (PKA) exerts opposing effects on GABA_{A} receptor adaptations during brief ethanol exposure. Cerebral cortical neurons from day 0–1 rat pups were tested after 18 days in culture. Receptor trafficking was assessed by Western blot analysis, and functional changes were measured using whole-cell patch-clamp recordings of evoked and miniature inhibitory postsynaptic current (mIPSC) responses. One-hour ethanol exposure increased membrane-associated PKC and PKA, but steady-state GABA_{A} \alpha1 subunit levels were maintained.

Activation of PKA by Sp-adenosine 3’,5’-cyclic monophosphothioate triethylamine alone increased GABA_{A} \alpha1 subunit surface expression and zolpidem potentiation of GABA responses, whereas coexposure of ethanol with the PKA inhibitor Rp-adenosine 3’,5’-cyclic monophosphothioate triethylamine decreased \alpha1 subunit expression and zolpidem responses. Exposure to the PKC inhibitor calphostin-C with ethanol mimicked the effect of direct PKA activation. The effects of PKA modulation on mIPSC decay \tau were consistent with its effects on GABA currents evoked in the presence of zolpidem. Overall, the results suggest that PKA acts in opposition to PKC on \alpha1-containing GABA_{A} receptors, mediating the GABAergic effects of ethanol exposure, and may provide an important target for the treatment of alcohol dependence/wrathdrawal.

Introduction

Ethanol elicits a number of adaptations in GABAergic signaling following both acute and chronic exposure. Evidence suggests that acute ethanol intoxication increases overall GABAergic inhibition, whereas chronic ethanol leads to deficits in GABA functioning [reviewed in Kumar et al. (2004, 2009)]. Numerous studies suggest that the major changes associated with GABAergic deficits following chronic ethanol exposure include a decrease in surface expression of GABA_{A} receptor \alpha1 subunits in both the cerebral cortex (Devaud et al., 1997; Kumar et al., 2003) and hippocampus (Cagetti et al., 2003; Liang et al., 2004, 2006, 2007). Chronic ethanol exposure produces a withdrawal syndrome upon discontinuation of ethanol that is mimicked, in part, by genetic deletion of \alpha1 subunits in mice that were never exposed to ethanol.

This suggests that the loss of GABA_{A} \alpha1 receptor surface expression is involved in tremor and enhanced seizure susceptibility associated with ethanol dependence (Kralic et al., 2002, 2005). Additionally, similar alterations in GABA_{A} \alpha1 subunit levels are found in other disorders, including models of epilepsy and benzodiazepine tolerance (Chen et al., 1999; Zeng and Tietz, 1999; Gonzalez and Brooks-Kayal, 2011). Therefore, a better understanding of GABA_{A} receptor regulation following ethanol exposure may provide both valuable insights into the general mechanism of GABA_{A} receptor regulation as well as potential therapeutic targets for pathologies linked to these disorders.

Recently, we and others have shown that GABA_{A} receptor adaptations to ethanol are recapitulated in vitro following a brief ethanol exposure in cultured cortical and hippocampal neurons (Kumar et al., 2010; Shen et al., 2011; Werner et al., 2011). The effect of ethanol is dependent upon the selective activation of protein kinase C (PKC) \gamma to induce the internalization of GABA_{A} \alpha1 subunits (Kumar et al., 2010), consistent with the ability of ethanol to activate PKC\gamma and reduce GABA_{A} \alpha1 subunit surface expression in vivo. However, there

Acknowledgments

This work was supported by the National Institutes of Health [Grants AA011605, AA015409, and AA007573]; and the Bowles Center for Alcohol Studies.

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dx.doi.org/10.1124/jpet.112.201954.

ABBREVIATIONS: ANOVA, analysis of variance; CalC, calphostin-C; mIPSC, miniature inhibitory postsynaptic current; PBS, phosphate-buffered saline; PKA, protein kinase A; PKC, protein kinase C; Rp-cAMP, Rp-adenosine 3’,5’-cyclic monophosphothioate triethylamine; Sp-cAMP, Sp-adenosine 3’,5’-cyclic monophosphothioate triethylamine.

http://dx.doi.org/10.1124/jpet.112.201954
is a mismatch between the time-dependent effects of ethanol on PKCγ and GABA₆α₁ receptors, suggesting the involvement of other mechanisms (Kumar et al., 2010).

Ethanol has long been known to directly activate protein kinase A (PKA) (Dohrman et al., 1996). In vivo studies implicated PKA as playing a role in the behavioral effects of ethanol (Thiele et al., 2000; Pandey et al., 2003; Lai et al., 2007). Additionally, PKA has been shown to directly phosphorylate and modulate GABA₆ receptor activity (Ives et al., 2002; Brandon et al., 2003). Recently, we found that ethanol dose- and time-dependent increases of PKA membrane levels in rat cerebral cortex, which corresponded to increased GABA₆α₁ subunit expression (Kumar et al., 2012). The precise physiological consequences of ethanol regulation of GABAergic inhibition via PKA, however, are unclear. As recent studies from our laboratory suggest that both PKC and PKA acti-

vations may influence GABA receptor activity during ethanol exposure, we investigated the dualistic role of PKA and PKC in modulating the actions of ethanol on GABA₆ receptor α₁ subunit expression and function in cortical cultured neurons.

Materials and Methods

Cultured Cerebral Cortical Neurons. All experiments were conducted in accordance with guidelines from the National Institutes of Health and Institutional Animal Care and Use Committee at the University of North Carolina. Cultured cerebral cortical neurons were isolated as described elsewhere (Kumar et al., 2010). Briefly, mixed-sex rat pups from Sprague-Dawley breeding pairs (Harlan, Indianapolis, IN) were decapitated on postnatal day 0–1. Brains were rapidly dissected and the cerebral cortices were isolated. Cortical halves were minced into fine pieces, and tissue was incubated in CO₂-independent media containing papain (50 U/ml) (Worthington, Lake-

wood, NJ) and L-cysteine and DNase (both from Sigma-Aldrich, St. Louis, MO) for 30 minutes at 37°C. Tissue pieces were gently washed and the cerebral cortices were isolated. Cortical halves were minced into fine pieces, and tissue was incubated in CO₂-independent media containing papain (50 U/ml) (Worthington, Lake-

wood, NJ) and L-cysteine and DNase (both from Sigma-Aldrich, St. Louis, MO) for 30 minutes at 37°C. Tissue pieces were gently washed followed by gentle trituration in Dulbecco’s modified Eagle’s medium (Gibco, Grand Island, NY) containing 10% horse serum, penicillin-
streptomycin, and DNase. Cells used for biochemistry were plated onto poly-D-lysine–coated flasks, while cells used for electrophysiology were plated onto poly-D-lysine–coated cover slips in 12-well plates. Cells were maintained in a 5% CO₂ humidified incubator. After day 3, cells were fed with serum-free medium containing B27 and penicillin-
streptomycin (10,000 U/ml; final concentration, 50 U per flask). Media were changed twice per week with no more than one-third of the media being removed during exchanges. For all experiments, penicillin-
streptomycin was removed from cultures on day 14 to prevent interactions with GABA₆ receptors. Cultures were maintained for at least 17 days before conducting experiments, as prior studies determined that GABA₆ receptor expression was stable between 15 and 19 days in vitro.

Ethanol and Drug Exposure. Cultured cells were exposed to 50 mM ethanol and placed in a plastic chamber within the incubator. A beaker of water with 50 mM ethanol was used to maintain stable ethanol concentrations in the chamber. Control cells were exposed to an equivalent amount of water and placed in a vapor chamber with a beaker containing water. Cells were exposed to ethanol for various times (0–60 minutes). To examine PKA involvement, the PKA acti-

vator Sp-adenosine 3’,5’-cyclic monophosphothioate triethylamine (Sp-cAMP) (70 μM) and the PKA inhibitor Rp-adenosine 3’,5’-cyclic monophosphothioate triethylamine (Rp-cAMP) (50 μM) were added to the cell media. These doses were chosen based on previous studies (Zhang and Pandey, 2003). To examine PKC involvement, the PKC inhibitor calphostin-C (CalC) (0.3 μM in 0.1% dimethyl sulfoxide, final concentrations) was used as previously described (Kumar et al., 2010).

P2 Fractionation and Biotinylation. After experiments, the reactions were stopped by placing the flasks on ice. Cells were washed with cold phosphate-buffered saline (PBS), scraped, centrifuged at 1000g for 18 minutes, and stored at −80°C until fractionation. Cell pellets were homogenized in 0.32 M sucrose and centrifuged at 1000g for 10 minutes. The supernatant was then centrifuged twice for 30 minutes at 12,000g. The final pellet was resuspended in PBS. Protein concentrations for the isolated P2 fraction were made using the bicinchoninic acid protein assay kit (Thermo Fisher Scientific, Waltham, MA). Biotinylation experiments were performed as previously described (Kumar et al., 2010). Briefly, cells were washed twice with ice-cold PBS, followed by addition of sulfoconcanimimidyl 2-biotinamido)-ethyl-1,3-dithiopropionate diluted in PBS, and incubated for 30 minutes at 4°C. Unbound biotin was inactivated using a quenching solution. Cells were scraped and spun three times at 500g in Tris-buffered saline. Biotin-labeled (surface) and flow-through (cytosolic) proteins were separated using NeutrAvidin slurry (Thermo Fisher Scientific). Biotinylated proteins were eluted from the beads by incubation for 60 minutes at 22°C in Laemmli sodium dodecyl sulfate polyacrylamide gel electrophoresis sample buffer. Samples were then subjected to gel electrophoresis and Western blotting.

Western Blot Analysis. GABA₆ receptor α₁ subunits, PKA subunits, and PKC isoforms were analyzed by Western blotting as described elsewhere (Kumar et al., 2010). Protein samples were subjected to sodium dodecyl sulfate polyacrylamide gel electrophoresis using Novex Tris-Glycine (8–16%) gels and transferred to polyvinyl-
diene difluoride membranes (Invitrogen, Carlsbad, CA). Membranes were probed with GABA₆ receptor α₁ subunit (Millipore, Billerica, MA) or PKA RIα, RIβ, or PKC-Ω (BD Biosciences, Franklin Lakes, NJ) antibodies. Blots were then exposed to an antibody for α2-actin for normalization. Proteins were detected with enhanced chemilumine-
sence (GE Healthcare, Amersham, UK). Membranes were exposed to film under nonsaturating conditions. Densitometric analysis was conducted using NIH Image 1.57 (Bethesda, MD). Comparisons were made within blots and expressed as % averaged control values. Statistics were conducted using analysis of variance (ANOVA) or Student’s t test.

Electrophysiology. Whole-cell voltage clamp recordings were used to assess evoked currents and miniature inhibitory postynaptic currents (mIPSCs). Electrodes were pulled using a PP-830 (Narishige, Tokyo, Japan) and fire-polished to a resistance of 2–3 MΩ. Intracellular solution contained 150 mM KCl, 3.1 mM MgCl₂, 15 mM HEPES, 5 mM KATP, 5 mM EGTA, and 15 mM phosphocreatine, adjusted to pH 7.4 with KOH, while extracellular solution contained 145 mM NaCl, 5 mM KCl, 10 mM HEPES, 2 mM CaCl₂, 1 mM MgCl₂, 5 mM sucrose, and 10 mM glucose, adjusted to pH 7.4 with NaOH. For mIPSC recordings, the extracellular solution also contained 6-cyano-7-
nitroquinoxaline-2,3-dione (10 μM) (Sigma-Aldrich), d-2-amino-5-
phosphopentonic acid (40 μM) (Tocris Bioscience, Bristol, UK), and tetrodotoxin (1 μM) (Sigma-Aldrich). Membrane potential was held at −60 mV, and currents were recorded with an Axopatch 1D (Axon Instruments, Union City, CA) amplifier. Data were collected using Clampex software (Axon Instruments). Drugs were diluted in the extracellular solution and applied using a U-tube apparatus. Zolpidem (100 nM) was coapplied with GABA (1 or 10 μM) to observe potentiation. Potentiation by zolpidem is expressed as the current in response to (GABA+zolpidem/GABA alone × 100). Dose-response curves were generated from GABA-evoked responses at 1, 3, 10, 30, 100 μM, and 1 mM GABA. Current amplitudes were normalized to the averaged control current response to 1 mM GABA and fit using GraphPad Prism software (GraphPad Software, La Jolla, CA) with the sigmoidal dose-response equation:

\[ Y = \min + \left( \max - \min \right) / \left[ 1 + 10^{\left( \log EC_{50} - X \right)} \right] \]

mIPSCs were analyzed using the Mini-Analysis software (version 5.6.4; Synaptosoft, Decatur, GA). mIPSCs were recorded for a minimum of 3 minutes. Minimum threshold detection was set to 5 pA.
Results

PKA Activation by Ethanol Modulates GABA<sub>A</sub> Receptor Trafficking and Activity. Cultured cerebral cortical neurons were exposed to ethanol (50 mM) for 1 hour to test for its effects on membrane expression of GABA<sub>A</sub> α1 subunit and protein kinase levels (Fig. 1). Whereas 4-hour ethanol exposure produces a decrease in GABA<sub>A</sub> α1 subunit (Kumar et al., 2010), no effects on this subunit are observed at the 1-hour time point (Fig. 1A). However, 1-hour ethanol exposure produced a significant increase in the abundance of both PKCγ (78.1% ± 21.0%; n = 7; P < 0.05, Student’s t test) (Fig. 1B) and the PKA regulatory subunits RIIα (35.5% ± 12.7%; n = 6; P < 0.05, Student’s t test) (Fig. 1C) and RIIβ (36.4% ± 11.1%; n = 6; P < 0.05, Student’s t test) (Fig. 1D) in the P2 fraction. Table 1 provides a comparison of the GABA<sub>A</sub> α1 and protein kinase trafficking changes induced by 1-hour and 4-hour ethanol exposure in cerebral cortical neurons. Whereas GABA<sub>A</sub> α1 membrane levels are unchanged at 1 hour and decreased following 4-hour ethanol, PKCγ levels are elevated at both time points. Conversely, whereas PKA RIIα and RIIβ are elevated at the 1-hour time point, PKA levels return to baseline after 4-hour ethanol (Table 1).

To determine the effects of ethanol that are mediated by PKA, GABA<sub>A</sub> receptor subunit levels were assessed after either direct activation of PKA or ethanol exposure in the presence of a PKA inhibitor. Additionally, whole-cell patch-clamp recordings were used to measure functional changes in GABA<sub>A</sub> receptor electrophysiological responses. GABA (1–1000 μM) responses were first determined, and then zolpidem (100 nM) enhancement of GABA (10 μM) responses was used as a pharmacological indicator for altered synaptic GABA<sub>A</sub> receptor activity (Liang et al., 2004; Kumar et al., 2010). Currents evoked by GABA alone were compared with currents evoked by coapplication of GABA + zolpidem to measure percent potentiation.

Exposure to the PKA activator Sp-cAMP (50 μM) for 1 hour produced a significant increase in GABA<sub>A</sub> α1 subunits relative to control values in the P2 fraction (58.4% ± 13.7%; n = 7; P < 0.05, Student’s t test) (Fig. 2A), with a corresponding increase in surface biotinylated protein (50.48% ± 18.45%; n = 5; P < 0.05, Student’s t test) (Fig. 2B) and decrease in the cytosolic fraction (54.03% ± 10.74%; n = 5; P < 0.05, Student’s t test) (Fig. 2C). Sp-cAMP exposure had no effect on the EC<sub>50</sub> or amplitude of GABA-evoked responses (Fig. 2D) or whole-cell GABA-evoked current amplitude at the dose used to test zolpidem enhancement of GABA responses (Fig. 2E). Sp-cAMP exposure did, however, increase zolpidem potentiation of GABA responses by 78.1% ± 9.4% (n = 6 per group; Student’s t test, P < 0.05) (Fig. 2, F and G) compared with control cells. Currents evoked over the course of 1 hour during Sp-cAMP treatment were compared with vehicle conditions using a double exponential fit for the average of the mIPSCs in a single recording. Numerical data are presented as mean ± S.E.M. Statistics were conducted using ANOVA or Student’s t test.

![Fig. 1](https://example.com/fig1.png)

One-hour ethanol (EtOH) (50 mM) alters expression of protein kinase subunits in the P2 fraction of cultured cortical neurons. Cortical neurons were exposed to EtOH (50 mM for 60 minutes), followed by preparation of P2 fractions. Western blot analysis of P2 fractions of cortical neurons revealed that P2 fraction levels of GABA<sub>A</sub> α1 were unchanged (A), whereas PKCγ subunit levels were increased by 78.1% ± 25.2% (B), PKA RIIα subunit levels were increased by 35.5% ± 12.7% (C), and PKA RIIβ subunit levels were increased by 36.4% ± 11.1% (D) following ethanol exposure. Graphs show the mean ± S. E.M. of percent control optical density (OD) values normalized to β-actin levels (n = 4–7 per group). *P < 0.05 compared with vehicle (Student’s t test).
exposure revealed that direct PKA activation resulted in a rapid increase in potentiation by zolpidem that was sustained over the course of the hour ($n = 4$; repeated-measures ANOVA, $f = 22.03$, $P < 0.05$, significantly increased at $t = 12–60$ minutes, Bonferroni post-test, $P < 0.05$), whereas current amplitude was stable for currents evoked under control conditions (Fig. 3).

Although ethanol alone did not significantly alter GABAA $\alpha 1$ levels after 1 hour, coexposure of ethanol and the PKA inhibitor Rp-cAMP decreased GABAA $\alpha 1$ membrane levels by 33% ($n = 4$; one-way ANOVA, $f = 4.031$, $P < 0.05$, Newman-Keuls post-test, $P < 0.05$) (Fig. 4A). Ethanol, ethanol + Rp-cAMP, or Rp-cAMP exposure had no effect on the GABA dose response (Fig. 4B) or GABA-evoked current amplitude (Fig. 4C). Reduced membrane levels of $\alpha 1$ subunits corresponded to reduced zolpidem potentiation of GABA responses in ethanol + Rp-cAMP–exposed cells ($n = 11$; one-way ANOVA, $f = 4.031$, $P < 0.05$, Newman-Keuls post-test, $P < 0.05$) (Fig. 4D and E). Rp-cAMP exposure alone had no effect on GABAA $\alpha 1$ subunit levels or zolpidem potentiation.

**Inhibition of PKC in the Presence of Ethanol Mimics Direct PKA Activation.** As ethanol is known to activate PKC and inhibition of PKC prevents the GABAergic changes seen after 4-hour ethanol exposure (Kumar et al., 2010; Werner et al., 2011), P2 fractions levels of GABAA subunits are provided in Table 1.

<table>
<thead>
<tr>
<th>Protein</th>
<th>1-H Ethanol</th>
<th>4-H Ethanol</th>
</tr>
</thead>
<tbody>
<tr>
<td>GABAA $\alpha 1$</td>
<td>109.4 ± 9.6%</td>
<td>↓ 59.8 ± 15.0%*</td>
</tr>
<tr>
<td>PKC $\gamma$</td>
<td>↑ 178.1 ± 21.0%*</td>
<td>↑ 152.3 ± 19.0%*</td>
</tr>
<tr>
<td>PKA RIIa</td>
<td>↑ 135.5 ± 12.7%*</td>
<td>97.1 ± 5.3%</td>
</tr>
<tr>
<td>PKA RIIb</td>
<td>↑ 136.4 ± 11.1%*</td>
<td>100.7 ± 4.2%</td>
</tr>
</tbody>
</table>

* $P < 0.05$ compared with controls, Student’s t test.

**TABLE 1**
Comparison of effects of ethanol at 1 and 4 hours on P2 fraction protein levels
Data for 4-hour time point levels of GABAA $\alpha 1$ and PKC$\gamma$ are from Kumar et al. (2010).

Although ethanol alone did not significantly alter GABAA $\alpha 1$ levels after 1 hour, coexposure of ethanol and the PKA inhibitor Rp-cAMP decreased GABAA $\alpha 1$ membrane levels by 33% ($n = 4$; one-way ANOVA, $f = 12.42$, $P < 0.05$, Newman-Keuls post-test, $P < 0.05$) (Fig. 4A). Ethanol, ethanol + Rp-cAMP, or Rp-cAMP exposure had no effect on the GABA dose response (Fig. 4B) or GABA-evoked current amplitude (Fig. 4C). Reduced membrane levels of $\alpha 1$ subunits corresponded to reduced zolpidem potentiation of GABA responses in ethanol + Rp-cAMP–exposed cells ($n = 11$; one-way ANOVA, $f = 4.031$, $P < 0.05$, Newman-Keuls post-test, $P < 0.05$) (Fig. 4D and E). Rp-cAMP exposure alone had no effect on GABAA $\alpha 1$ subunit levels or zolpidem potentiation.

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PKA Activation by Ethanol Regulates Zolpidem Modulation of mIPSC Decay \( \tau_2 \). As ethanol exposure has been shown to alter mIPSC decay kinetics, which is related to changes in GABA\( _{\alpha} \) receptor subunit expression (Liang et al., 2006; Fleming et al., 2009; Werner et al., 2011), recordings of mIPSCs were made to further investigate the functional consequences of ethanol activation of PKA on synaptic GABA\( _{\alpha} \) receptor signaling. Although there appeared to be a slight shift in the mIPSC decay kinetics suggestive of an altered synaptic GABA\( _{\alpha} \) receptor expression profile, there was not a significant direct effect of 1 hour ethanol and/or PKA modulation on GABA mIPSC kinetics (Fig. 6A; Table 2). To further investigate the potential for receptor subtype–specific effects on mIPSCs, recordings were also made in the presence of 100 nM zolpidem. Under control conditions zolpidem increased decay \( \tau_2 \) as expected (comparison of control with and without zolpidem, \( P < 0.05 \), Student’s \( t \) test). Further, decay \( \tau_2 \) in the presence of zolpidem (Fig. 6B; Table 2) was decreased after ethanol + Rp-cAMP exposure (24.7% ± 3.2%; \( n = 6 \)) and increased after Sp-cAMP exposure (68.8% ± 9.0%; \( n = 6 \)) relative to controls (46.1% ± 3.7%; \( n = 8 \); one-way ANOVA, \( f = 9.673, P < 0.05 \), Newman-Keuls post-test, \( P < 0.05 \) for both comparisons). No other mIPSC characteristics were altered in the presence of zolpidem following modulation of PKA activity (Table 2).

Discussion

The present results demonstrate that ethanol activation of PKA plays an active role in GABA\( _{\alpha} \) receptor trafficking and function. PKA activation results in an increase in GABA\( _{\alpha} \) subunit expression in P2 and biotinylated fractions of surface receptors in cultured cortical neurons. The finding that these alterations corresponded to functional changes in zolpidem enhancement of GABA responses corroborates this conclusion. Additionally, our results highly implicate oppositional roles of PKA and PKC in GABA\( _{\alpha} \) receptor regulation. Ethanol is known to activate both PKA and PKC pathways, and our past results coupled with the present studies indicate that such changes in activity are accompanied by increases in PKA and PKC abundance in the P2 fraction. We demonstrate that inhibiting the activity of either kinase pathway in the presence of ethanol results in GABA\( _{\alpha} \) subunit alterations that are dependent on the sum of the activity of these protein kinase pathways. Specifically, inhibition of PKC in the presence of ethanol results in increased GABA\( _{\alpha} \) surface expression, similar to that observed following exposure to PKA activators alone. Furthermore, a decrease in GABA\( _{\alpha} \) receptor \( \alpha_1 \) subunit levels similar to that found in models of ethanol dependence in vivo (Devau et al., 1997; Cagetti et al., 2003; Liang et al., 2004) or 4-hour ethanol exposure in vitro (Kumar et al., 2010; Werner et al., 2011) could be observed after 1-hour ethanol exposure in the presence of a PKA antagonist.

The results suggest that ethanol activates at least two opposing pathways in the cerebral cortex: PKA and PKC. Whereas PKC\( \gamma \) activation results in decreased GABA\( _{\alpha} \) receptor \( \alpha_1 \) subunit (Kumar et al., 2010), PKA appears to counteract these changes. Such opposition is consistent with previous studies that have found an apparent antagonistic role of PKA and PKC working in other areas of the central nervous system (Vaello et al., 1994; Brandon et al., 2000; Grey and Chang, 2003; Liang et al., 2004) or 4-hour ethanol exposure in vitro (Kumar et al., 2010; Werner et al., 2011) could be observed after 1-hour ethanol exposure in the presence of a PKA antagonist.

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The data further suggest that these kinases are under time-dependent regulation by ethanol. Although PKA and PKC are both active at 1 hour of ethanol exposure, no overall change in GABA_{A} \alpha_{1} subunit expression is observed. By 4 hours, however, PKA activity has returned to baseline while PKC remains active, and trafficking of GABA_{A} \alpha_{1} receptors is observed (Kumar et al., 2010; Werner et al., 2011). An increase in PKA translocation to the P2 synaptosomal region is consistent with ethanol-induced activation of PKA (Diamond and Gordon, 1997). Although the exact role of increased PKA subunits in the synaptosomal region is unclear, the effects of direct activation by Sp-cAMP, or inactivation by Rp-cAMP in the presence of ethanol, would suggest that ethanol is increasing overall catalytic activity by PKA. Future studies might investigate the specific phosphorylation states regulating trafficking of \alpha_{1} subunits by the oppositional PKA and PKC activation by ethanol.

The present results extend several recent studies characterizing altered GABA_{A} regulation following ethanol exposure. These alterations include a shift in the normal synaptic and extrasynaptic GABA_{A} receptor trafficking. Studies in the hippocampus have found a decrease in synaptic \alpha_{1} and extrasynaptic \alpha_{4} receptors, and a corresponding increase in synaptic \alpha_{4} GABA_{A} receptors, following both acute (Liang et al., 2007) and chronic (Cagetti et al., 2003; Liang et al., 2004) exposure.
ethanol exposure, thereby producing an overall decrease in GABAergic inhibition and increasing central nervous system hyperexcitability. The present results suggest that these processes are conserved in the cerebral cortex as well (Kumar et al., 2010; Werner et al., 2011). The lack of an effect of brief (1-hour) ethanol exposure on GABA<sub>A</sub> α1 receptors in the present study is consistent with prior reports in cerebral cortex and in cultured cortical neurons (Kumar et al., 2003, Fig. 5. PKA and PKC activation by ethanol (EtOH) produces opposing effects on GABA<sub>A</sub> α1 expression and zolpidem potentiation of GABA responses. (A) Neurons were exposed to vehicle, EtOH (50 nM), or EtOH with CalC (0.3 μM) for 60 minutes, followed by preparation of P2 fractions and Western blot analysis. EtOH or CalC exposure alone did not alter GABA<sub>A</sub> receptor α1 subunit expression; however, EtOH exposure in the presence of the PKC inhibitor CalC increased GABA<sub>A</sub> receptor α1 subunit expression by 56% (one-way ANOVA, F = 11.91, P < 0.05, Newman-Keuls post-hoc test). (B and C) Whole-cell currents were evoked by application of GABA (1 μM) and zolpidem (100 nM) at 2-minute intervals over the course of 1 hour during exposure to EtOH (50 nM), EtOH and Rp-cAMP (50 μM), or EtOH and CalC (3 μM). Currents were stable for the 10-minute period prior to bath application of EtOH and during diffusion of CalC or Rp-cAMP via the recording pipette. Currents evoked by EtOH + CalC were significantly increased from 14–60 minutes (repeated-measures ANOVA, F = 3.863, P < 0.05, Bonferroni post-test). Currents evoked by EtOH + Rp-cAMP were significantly decreased at 8–60 minutes (repeated-measures ANOVA, F = 11.10, P < 0.01, Bonferroni post-test). (C) Representative whole-cell current traces elicited by GABA and zolpidem before (t = 0) and after (t = 60 minutes) EtOH and drug exposure. Data are presented as mean ± S.E.M.; n = 3–6 per group.

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Fig. 6. Ethanol (EtOH) and PKA modulation of GABA<sub>A</sub> mIPSC decay kinetics in the presence of zolpidem. Recordings were made in the presence of tetrodotoxin, 6-cyno-7-nitroquinoxaline-2,3-dione, and d-2-amino-5-phosphono pentanoic acid to pharmacologically isolate GABA mIPSCs. Representative averaged mIPSC traces, following exposure to vehicle (control) or drug and standardized for peak amplitude, are shown. (A) Representative control (no zolpidem) traces following control, EtOH, Sp-cAMP, or EtOH + Rp-cAMP exposure. (B) Representative traces in the presence of zolpidem (100 nM) following control, Sp-cAMP, or EtOH + Rp-cAMP exposure. Summarized data are shown in Table 2.
GABA<sub>A</sub> receptor epileptogenesis (Gonzalez and Brooks-Kayal, 2011). Insults such as ethanol exposure or processes associated with regulators of GABAergic inhibition following physiological receptors. Rather, these pathways may only become active focused on the GABA<sub>A</sub> due to the use of different model systems and the fact that we in the present study (Kittler and Moss, 2003). This is likely of protein kinases. Are secondary to regional differences in ethanol activation of GABA receptor function have been previously observed in inhibition may have been observed at higher concentrations of GABA. It is quite possible that effects of PKA or PKC observation that inhibition of PKA or PKC alone had no effect a receptors. The resulting amplitude was unchanged would suggest bidirectional regulation of GABA<sub>A</sub> receptors in cultured neurons, we used an IC<sub>50</sub> concentration of GABA. It is quite possible that effects of PKA or PKC inhibition may have been observed at higher concentrations of GABA; however, such an experiment would involve actions at additional receptor subtypes. Although effects of PKA on GABA<sub>A</sub> receptor function have been previously observed (Brandon et al., 2003; Lilly et al., 2003), this is the first evidence that PKA specifically regulates trafficking and function of zolpidem-sensitive GABA<sub>A</sub> α1 receptors. The observation that inhibition of PKA or PKC alone had no effect on α1 receptor abundance or function, however, suggests that these kinases do not constitutively regulate GABA<sub>A</sub> α1 receptors. Rather, these pathways may only become active regulators of GABAergic inhibition following physiological insults such as ethanol exposure or processes associated with epileptogenesis (Gonzalez and Brooks-Kayal, 2011). Although our present results demonstrate modulation of GABA<sub>A</sub> receptor α1 subunit abundance by PKA in vitro, our previous results suggest the same processes occur in vivo (Kumar et al., 2012). Recently, we found that GABA<sub>A</sub> α1 levels in rat cerebral cortex were increased following an acute ethanol injection, concurrent with an increase in PKA, whereas PKC was unchanged. Further, behavioral studies have well established that PKA is a key mediator of ethanol sensitivity. Infusion of Sp-cAMP into the lateral ventricles prior to systemic ethanol administration increased the duration of loss of righting reflex (Kumar et al., 2012). Conversely, inhibition of PKA prior to ethanol administration decreased loss of righting reflex duration (Lai et al., 2007) and withdrawal-induced anxiety (Pandey et al., 2003). Studies utilizing mutant mouse lines with reduced PKA activity mimic results found with pharmacological inhibition of PKA (Thiele et al., 2000; Naassila et al., 2002; Kim et al., 2011). The precise role of PKA in mediating these behaviors is complex, however, as some studies have found increased ethanol sensitivity in animals with diminished PKA activity (Wand et al., 2001; Yang et al., 2003; Maas et al., 2005). Although the precise role remains equivocal, collectively these studies clearly establish the importance of PKA activation in mediating the behavioral effects of ethanol, potentially through GABA<sub>A</sub> receptor regulation. The present results underscore the clinical relevance of understanding the role of PKA in modulating the effects of ethanol for the development of drugs for the treatment of alcoholism. The relatively rapid time course over which changes in zolpidem potentiation were observed suggests a posttranslational mechanism of GABA<sub>A</sub> receptor regulation (Brandon et al., 2002). Previous studies in cultured cerebral cortical neurons have found changes in GABA<sub>A</sub> receptor activity via phosphorylation and dephosphorylation to be due entirely to changes in channel gating and conductance rather than channel number (Brandon et al., 2000). The fact that the functional changes were observed prior to alterations in surface receptor expression suggest that multiple mechanisms of GABA regulation may be involved, including both direct effects on channel conductance as well as receptor trafficking. Further studies investigating single-channel conductance states and utilizing phosphorylation state–dependent antibodies will help to elucidate these mechanisms. Additionally, the observation that whole-cell GABA-evoked current amplitude was unchanged would suggest bidirectional regulation of GABA receptor subtypes by PKA, as well as ethanol. Thus, whereas PKA activation leads to increased surface expression of GABA<sub>A</sub> α1 receptors, there is likely a concurrent decrease in other subtypes. Previous studies have observed bidirectional regulation of synaptic GABA<sub>A</sub> α1– and α4-containing receptors by PKCγ (Kumar et al., 2010; Werner et al., 2011), and studies are currently under way to investigate bidirectional regulation of GABA<sub>A</sub> α4 receptors by PKA. Overall, the present study elucidates a novel role for PKA in the subcellular pathways mediating the effects of ethanol. Although PKC and PKA play important roles in altered GABA<sub>A</sub> receptor trafficking following ethanol exposure, it is possible that other kinases or phosphatases are also active. In particular, ethanol-induced adaptations in other brain regions may be governed by different subcellular mechanisms, which could, in part, account for some of the brain region–specific effects of ethanol. This area requires further

### Table 2

GABA<sub>A</sub> mIPSC kinetics following exposure to PKA modulators and ethanol  

<table>
<thead>
<tr>
<th>Measure</th>
<th>Control</th>
<th>Ethanol</th>
<th>Ethanol + Rp-cAMP</th>
<th>Sp-cAMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise time (ms)</td>
<td>3.6 ± 1.5</td>
<td>1.2 ± 0.8</td>
<td>4.0 ± 1.5</td>
<td>1.3 ± 0.9</td>
</tr>
<tr>
<td>Decay 90–37% (ms)</td>
<td>14.4 ± 2.6</td>
<td>21.7 ± 1.6</td>
<td>14.9 ± 2.2</td>
<td>16.7 ± 2.6</td>
</tr>
<tr>
<td>Half-width (ms)</td>
<td>12.6 ± 2.5</td>
<td>20.1 ± 0.7</td>
<td>14.5 ± 3.2</td>
<td>16.4 ± 2.0</td>
</tr>
<tr>
<td>Amplitude (pA)</td>
<td>25.3 ± 0.8</td>
<td>23.4 ± 1.0</td>
<td>23.2 ± 1.1</td>
<td>21.8 ± 1.8</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>2.6 ± 0.9</td>
<td>1.6 ± 0.2</td>
<td>1.6 ± 0.5</td>
<td>1.5 ± 0.3</td>
</tr>
<tr>
<td>Decay τ1 (ms)</td>
<td>13.2 ± 2.4</td>
<td>18.3 ± 2.0</td>
<td>15.0 ± 3.2</td>
<td>16.8 ± 1.7</td>
</tr>
<tr>
<td>Decay τ2 (ms)</td>
<td>31.0 ± 6.4</td>
<td>36.6 ± 5.8</td>
<td>26.3 ± 2.5</td>
<td>45.6 ± 10</td>
</tr>
<tr>
<td>Decay τ2 (ms) with zolpidem</td>
<td>46.1 ± 3.7**</td>
<td>46.2 ± 6.0</td>
<td>24.7 ± 3.2**</td>
<td>68.8 ± 9.0**</td>
</tr>
<tr>
<td>n</td>
<td>8</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>

**P < 0.05 compared with control decay τ2 (without zolpidem), Student's t test; *P < 0.05 compared with controls with zolpidem, one-way ANOVA, Newman-Keuls post-test.  

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study to fully elucidate the physiology of ethanol intoxication and withdrawal. Nonetheless, the current results suggest that PKA activation may delay some ethanol-induced adaptations in GABAergic signaling. Additionally, PKA may provide a promising target for the development of drugs aimed at restoring normal GABA<sub>A</sub> receptor function for the treatment of multiple pathologies involving similar GABA<sub>A</sub> receptor adaptations, including alcohol dependence, epilepsies, and benzodiazepine abuse.

Acknowledgments

The authors thank Hugh E. Criswell for helpful discussions and Todd K. O’ Buckley for expert technical assistance.

Authorship Contributions

Participated in research design: Carlson, Kumar, Morrow.
Conducted experiments: Carlson, Kumar, Comerford.
Performed data analysis: Carlson, Kumar, Comerford.
Wrote or contributed to the writing of the manuscript: Carlson, Werner, Comerford, Morrow.

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