Ethanol Modulates Synaptic and Extrasynaptic GABA<sub>A</sub> Receptors in the Thalamus

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ABSTRACT

Drinking alcohol is associated with the disturbance of normal sleep rhythms, and insomnia is a major factor in alcoholic relapse. The thalamus is a brain structure that plays a pivotal role in sleep regulation and rhythmicity. A number of studies have implicated GABA<sub>A</sub> receptors (GABA<sub>A</sub>-Rs) in the anxiolytic, amnestic, sedative, and anesthetic effects of ethanol. In the present study, we examined the effects of ethanol on both synaptic and extrasynaptic GABA<sub>A</sub>-Rs of relay neurons in the thalamus. We found that ethanol (≥50 mM) elicits a sustained current in thalamocortical relay neurons from the mouse ventrobasal thalamus, and this current is associated with a decrease in neuronal excitability and firing rate in response to depolarization. The steady current induced by ethanol was totally abolished by gabazine and was absent in relay neurons from GABA<sub>A</sub>-R<sub>α<sub>4</sub></sub> subunit knockout mice, indicating that the effect of ethanol is to enhance tonic GABA<sub>A</sub>-mediated inhibition. Ethanol (50 mM) enhanced the amplitude of tonic inhibition by nearly 50%. On the other hand, ethanol had no effect on spontaneous or evoked inhibitory postsynaptic currents (IPSCs) at 50 mM but did prolong IPSCs at 100 mM. Ethanol had no effect on the paired-pulse depression ratio, suggesting that the release of GABA from presynaptic terminals is insensitive to ethanol. We conclude that ethanol, at moderate (50 mM) but not low (10 mM) concentrations, can inhibit thalamocortical relay neurons and that this occurs mainly via the actions of ethanol at extrasynaptic GABA<sub>A</sub>-Rs containing GABA<sub>A</sub>-R<sub>α<sub>4</sub></sub> subunits.

Drinking alcohol can promote the onset of sleep, but it can also disrupt the normal sleep pattern, increase nocturnal awakenings, and reduce sleep quality (Drummond et al., 1998). Sleep disturbance caused by chronic alcohol can play a role in the progression of alcoholism, and poor sleep quality is often cited as a factor in alcoholic relapse (Brower et al., 1998; Brower, 2001). Inhibition in the thalamus plays an important role in the normal regulation of sleep cycles (Steriade, 2000; Huguenard and McCormick, 2007; Jia et al., 2007) and may, therefore, be involved in both the sedative effects of acute alcohol and in the development of alcoholism.

The inhibitory neurotransmitter GABA has long been implicated in the anxiolytic, amnestic, sedative, and anesthetic effects of alcohol. A large number of studies have investigated the interactions of alcohol with GABA<sub>A</sub> receptors (GABA<sub>A</sub>-Rs). The standard forms of recombinant GABA<sub>A</sub>-Rs that are found at GABAergic synapses (α<sub>1</sub>β<sub>2</sub>γ<sub>2</sub> and α<sub>2</sub>β<sub>2</sub>γ<sub>2</sub> subtypes) are modulated only by >60 mM ethanol (Sigel et al., 1993; Mihic et al., 1997). Most investigators have failed to observe direct postsynaptic actions of alcohol (<60 mM) on GABA-mediated inhibitory postsynaptic currents (IPSCs) in brain slices, except at high levels (Ariwodola and Weiner, 2004; Weiner and Valenzuela, 2006). In several brain areas, however, ethanol has been shown to facilitate synaptic inhibition by a presynaptic mechanism, for example, in the amygdala (Roberto et al., 2003, 2004; Roberto and Siggins, 2006; Zhu and Lovinger, 2006), cerebellum (Carta et al., 2004; Hanchar et al., 2005; Ming et al., 2006; Kelm et al., 2007), hippocampus (Ariwodola and Weiner, 2004; Sanna et al., 2004; Galindo et al., 2005), and nucleus accumbens (Nie et al., 2000; Crowder et al., 2002).

A novel form of “tonic inhibition” has also been described in the CNS, which is generated by the persistent activation of extrasynaptic GABA<sub>A</sub>-Rs (Semyanov et al., 2004; Farrant and Nusser, 2005; Mody, 2005). GABAergic tonic inhibition has been shown to regulate the excitability of individual neurons and the behavior of neural networks. Tonic inhibition is most often generated by activation of GABA<sub>A</sub>-Rs that...
contain δ subunits, which are normally located at extrasynaptic or perisynaptic sites (Nusser et al., 1998; Wei et al., 2003). Several laboratories have reported that extrasynaptic GABA_A-Rs containing δ subunits are sensitive to low concentrations (~30 mM) of alcohol (Sundstrom-Poromaa et al., 2002; Wallner et al., 2003, 2006; Wei et al., 2004; Hanchar et al., 2005, 2006; Santhakumar et al., 2006; Glykys et al., 2007); however, other laboratories have reported contradictory results (Carta et al., 2004; Borghese et al., 2006; Botta et al., 2007; Korpi et al., 2007).

Tonic inhibition also occurs in the relay neurons of the thalamus (Porrello et al., 2003; Belletti et al., 2005; Cope et al., 2005; Jia et al., 2005, 2005b; Chandra et al., 2006; Bright et al., 2007; Peden et al., 2008), where the extrasynaptic GABA_A-Rs contain α4, β2, and δ subunits (Belletti et al., 2005; Chandra et al., 2006). Thalamic extrasynaptic GABA_A-Rs have distinct pharmacological properties that differentiate them from synaptic GABA_A-Rs, consisting mainly of α1, β2, and γ2 subunits (Pirker et al., 2000; Browne et al., 2001; Jia et al., 2005). Several studies show that hypnotics and anesthetics are much more potent at thalamic extrasynaptic GABA_A-Rs than at synaptic receptors (Belletti et al., 2005; Cope et al., 2005; Jia et al., 2005; Chandra et al., 2006). Investigating the effects of alcohol on both synaptic and extrasynaptic inhibition in the thalamus should enhance our understanding of the mechanisms underlying the interaction between alcohol and sleep. Therefore, we examined the actions of ethanol on the function of GABA_A-Rs of thalamic cortical relay neurons in the mouse ventrobasal (VB) thalamus.

Materials and Methods

Electrophysiological Recordings in Brain Slices. Experiments were performed in accordance with institutional and federal guidelines, using mice between 23 and 60 days old (C57BL/6, Gabra4^+/−, and Gabra4^−/−) by methods we have described previously (Jia et al., 2005). The knockout (Gabra4^−/−) and wild-type (Gabra4^+/−) littermates used were age-matched and on the same genetic background (129 × 1/S1 × C57BL/6J hybrid; F2–F4 generations) (Chandra et al., 2006). The experimenters were blind to genotype.

Animals were anesthetized with halothane, and brains were removed and placed in ice-cold slicing solution, which contained 2.5 mM KCl, 26 mM NaHCO_3, 1.25 mM NaH_2PO_4, 220 mM sucrose, 11 mM glucose, 10 mM MgSO_4, and 0.5 mM CaCl_2, before horizontal slices (300 μm thick) were cut on a microslicer (VT 1000S; Leica, Wetzlar, Germany). Slices were perfused with carbogenated artificial cerebrospinal fluid, which contained 124 mM NaCl, 2.5 mM KCl, 2 mM MgSO_4, 2 mM CaCl_2, 26 mM NaHCO_3, 1.25 mM NaH_2PO_4, and 10 mM glucose. Whole-cell patch-clamp recordings from visually identified thalamic neurons were performed at room temperature as described previously (Jia et al., 2005). Intracellular solution for most voltage-clamp recordings contained 140 mM CsCl, 4 mM NaCl, 1 mM CaCl_2, 10 mM HEPES, pH adjusted to 7.25 with CsOH. For voltage-clamp recordings involving acamprosate, intracellular solution contained 130 mM CsCH_3SO_3, 8.3 mM NaCH_3SO_3, 1.7 mM NaCl, 1 mM CaCl_2, 10 mM HEPES, 2 mM ATP-Mg_2^+, 0.3 mM GTP-Na^+, and 10 mM HEPES, pH adjusted to 7.25 with CsOH. For voltage-clamp recordings containing acamprosate, intracellular solution contained 130 mM CsCl, 8.3 mM NaCH_3SO_3, 1.7 mM NaCl, 1 mM CaCl_2, 10 mM HEPES, 2 mM ATP-Mg_2^+, 0.3 mM GTP-Na^+, and 10 mM HEPES, pH adjusted to 7.25 with CsOH. Intracellular solution for current-clamp recordings contained 130 mM K^−-gluconate, 5 mM NaCl, 2 mM MgCl_2, 10 mM HEPES, 0.5 mM EGTA, 2 mM ATP-K^−, and 0.3 mM GTP-Na^+, pH adjusted to 7.25 with KOH. Spontaneous inhibitory post synaptic currents were recorded at −65 mV and isolated by bath application of 3 to 5 mM kynurenic acid (Jia et al., 2005), and evoked IPSCs were elicited by electrical stimulation (50 μs; 2 × threshold) with a bipolar metal electrode (FHC, Bowdoin, ME) located in the reticular thalamic nucleus. The interval between successive stimuli was long (>15 s) to prevent cumulative synaptic depression. Access resistance was monitored throughout the recording period and was less than 20 MΩ throughout.

Drugs and Data Analysis. Gabazine [4-[(4-amino-3-(4-methoxyphenyl)pyridazin-1-yl)butanoic acid hydrobromide], kynurenic acid [4-oxo-1H-quinoline-2-carboxylic acid], baclofen [4-amino-3-(4-chlorophenyl)-butanoic acid], and ethanol were purchased from Sigma (St. Louis, MO). Acamprosate calcium (3-acetamidopropane-1-sulfonic acid calcium salt) was obtained from Toronto Research Chemicals Inc. (North York, ON, Canada). Off-line analysis was performed using MiniAnalysis 5.5 (Synaptosoft, Decatur, GA), SigmaPlot 6.0 (SPSS, Chicago, IL), and Excel 2000 (Microsoft, Redmond, WA), as described in our previous publications. Tonic currents were measured as illustrated in Fig. 2C. The holding current was calculated by averaging an IPSC-free 5-ms section from every 100 ms of record. The all-points histograms were fitted with a Gaussian curve. The difference between the peaks of these Gaussian curves in the presence and absence of drug were calculated to determine the change of holding current. Spontaneous IPSCs were detected and analyzed using MiniAnalysis as described previously (Jia et al., 2006). Numeric data are expressed as mean ± S.E.M., except where indicated. The statistical significance of results was assessed using Student’s t test or one-way ANOVA, and a level of p < 0.05 was considered significant.

Results

Ethanol Decreases Excitability in Thalamic Relay Neurons via GABA_A-Rs. We began by investigating whether ethanol modulates tonic firing of action potentials in depolarized thalamocortical relay neurons (Sherman, 2001). The membrane potentials of VB neurons were maintained at around −60 mV by constant current injection. At this membrane potential, VB neurons were generally silent but displayed sustained AP firing in response to depolarizing current steps. Ethanol (50 mM) decreased the excitability of VB relay neurons (Fig. 1A) and shifted the input-output curve to the right. This effect of alcohol to inhibit neuronal excitability is dependent on GABA_A-Rs, because in the presence of gabazine (20 μM), a specific GABA_A-R antagonist, ethanol had no effect on the input-output relationship (Fig. 1B).

To facilitate the comparison of firing rates, the amplitude of the current step (500 ms duration) was adjusted in each neuron to induce ~10 APs, corresponding to a firing frequency of ~20 Hz. We then compared the number of APs evoked by depolarizing current steps before and after ethanol application. Ethanol (20 mM) failed to decrease firing rate (9.6 ± 1.5 versus 9.4 ± 1.6; p > 0.05, n = 5; Fig. 1C). In contrast, 50 mM ethanol significantly reduced the number of evoked APs from 10.9 ± 1.4 to 8.5 ± 1.4 (p < 0.01, n = 6; Fig. 1D). Preaplication of gabazine completely prevented the inhibitory effects of 50 mM ethanol on firing (p > 0.05, n = 5; Fig. 1E). These results demonstrate that a sedative-hypnotic concentration (50 mM) of ethanol can reduce the excitability of depolarized VB relay neurons mainly through a GABA_A-R mechanism.

Ethanol Enhances Tonic Inhibition in VB Neurons. We made whole-cell voltage-clamp recordings to explore the modulation by ethanol of synaptic and extrasynaptic GABA_A-Rs. First, we examined whether ethanol induces any change of the tonic current mediated by extrasynaptic GABA_A-Rs. At low concentrations (10–30 mM), ethanol induced no signifi-
A significant change of holding current (10 mM: 0.8 ± 0.3 pA, n = 12; 20 mM: 1.8 ± 0.7 pA, n = 18; 30 mM: 2.4 ± 1.2 pA, n = 10), but at higher concentrations (50–100 mM), ethanol elicited a steady and sustained current shift (50 mM: 9.5 ± 1.5 pA, n = 19; 100 mM: 19.0 ± 3.6 pA, n = 12; Fig. 2, A and B). In some experiments, we applied 20 μM gabazine following the application of 50 mM ethanol. Gabazine not only blocked the ethanol-induced current shift but also revealed the underly-

**Fig. 1.** Ethanol (50 mM) decreases the excitability of VB neurons via GABA<sub>A</sub>-Rs. A, representative current clamp traces demonstrate AP firing evoked by current steps (40–160 pA, duration 500 ms) in a VB neuron. After ethanol (50 mM) perfusion, AP firing decreased, and the input-output curve shifted rightwards. B, representative current clamp traces demonstrating AP firing evoked by current steps in the presence of gabazine (20 μM) in another VB neuron. Ethanol (50 mM) perfusion failed to change the input-output curves when GABA<sub>A</sub>-Rs were blocked. C, exemplar current trace demonstrating that 20 mM ethanol induced no change on firing rate evoked by depolarized current steps. On average, ethanol (20 mM) also makes no change on the numbers of APs (9.6 ± 1.5 versus 9.4 ± 1.6, p > 0.05, n = 5), N.S., not significant. D, pooled data show that 50 mM ethanol significantly reduced the number of evoked action potentials from 10.9 ± 1.4 to 8.5 ± 1.4 (**, p < 0.01, n = 6). E, when GABA<sub>A</sub>-Rs are blocked by gabazine, 50 mM ethanol fails to inhibit tonic action potential firing (12.5 ± 1.7 to 12.4 ± 1.9, p > 0.05, n = 5).
Enhanced tonic currents by 50 mM ethanol were due to enhancement of tonic inhibition mediated by extrasynaptic GABAA-Rs. We measured the tonic currents before and after ethanol perfusion, as shown in Fig. 2C, and the pooled data from all experiments (n = 12) were well fitted by a straight line (r = 0.98), with a slope of 1.50, indicating that 50 mM ethanol enhanced tonic currents by 50%.

Ethanol-Evoked Currents Are Absent in VB Neurons from Gabra4−/− Mice. We have previously demonstrated that extrasynaptic GABAA-Rs are absent from the thalamus of Gabra4−/− mice (Chandra et al., 2006) and, therefore, investigated the actions of ethanol in VB neurons from Gabra4−/− mice and their wild-type littermates (Fig. 3). Ethanol (50 mM) failed to induce any shift in baseline current in VB neurons from α4 knockout mice (1.7 ± 0.9 pA, n = 10). In contrast, wild-type neurons showed measurable current shifts in response to 50 mM ethanol (8.6 ± 2.6 pA, n = 6), which were comparable to ethanol-induced currents recorded from C57BL/6 mice. This difference between the genotypes was highly significant (p < 0.01). These results are consistent with the idea that low concentrations of ethanol selectively enhance the activity of extrasynaptic GABAA-Rs in VB neurons that contain αβ subunits (Jia et al., 2005; Chandra et al., 2006).

Acamprosate Enhances Tonic Inhibition in VB Neurons Only at High Concentrations. Our recent work has shown that taurine is also a potent agonist for thalamic extrasynaptic GABAA-Rs (Jia et al., 2008b). Acamprosate (3-acetamidopropane-1-sulfonic acid) is a taurine analog that has no effect on tonic currents (14.6 ± 3.8 pA, p < 0.05, n = 6, and 42.5 ± 6.8 pA, p < 0.01, n = 6, respectively; Fig. 4). These results are consistent with a recent report (Reilly et al., 2008) that shows that acamprosate at low, clinically relevant concentrations has no effect on αβ GABAA-Rs expressed in Xenopus laevis oocytes.
High Concentrations of Ethanol Prolong IPSC Decay Time. We investigated next whether ethanol changes the properties of IPSCs. Spontaneous inhibitory synaptic currents are readily observed in VB neurons and can be blocked by gabazine (data not shown), indicating that they are mediated by synaptic GABAA-Rs. The averaged data from this set of experiments (Fig. 5C) show that, at all of the three concentrations that we tested (20, 50, and 100 mM), ethanol induced no significant change in the frequency (percentage change: 20 mM: −3.2 ± 3.6%, n = 9; 50 mM: 3.8 ± 3.1%, n = 16; 100 mM: 7.0 ± 6.6%, n = 8) or the amplitude of spontaneous IPSCs (percentage change: 20 mM: −1.0 ± 2.3%, n = 9; 50 mM: −1.2 ± 2.4%, n = 16; 100 mM: 1.5 ± 4.5%, n = 8).

At 100 mM, ethanol did significantly increase the decay time of spontaneous IPSCs by 8.5 ± 2.0% (p < 0.01, n = 8).

We also compared evoked inhibitory synaptic currents before and after ethanol applications. Gabazine completely blocked evoked IPSCs (data not shown), suggesting that these were mediated by GABAA-Rs, and ethanol (20–100 mM) did not enhance the amplitude of evoked IPSCs (percentage change: 20 mM: 1.7 ± 1.4%, n = 7; 50 mM: 2.3 ± 3.1%, n = 8; 100 mM: 0.3 ± 2.5%, n = 13); only 100 mM ethanol increased the decay time of evoked IPSCs (percentage change: 20 mM: −0.5 ± 1.5%, n = 7; 50 mM: 5.8 ± 2.6%, n = 8; 100 mM: 13.6 ± 2.5%, p < 0.001, n = 13; Fig. 6, A and B). Ethanol (≤50 mM) does not appear to modulate the function of synaptic GABAA-Rs in VB neurons.

Ethanol Has No Presynaptic Effect on IPSCs in VB Neurons. In many parts of the CNS, alcohol alters synaptic inhibition via a presynaptic mechanism, often by an increase in frequency. These presynaptic effects have been reported in the amygdala and cerebellum, for example (Siggins et al., 2005; Breeze et al., 2006; Roberto et al., 2006; Weiner and Valenzuela, 2006). As mentioned above, we recorded evoked IPSCs of VB neurons and used the well described paired-pulse stimulation protocol (Zalutsky and Nicoll, 1990), which is widely used to detect a change in transmitter release from presynaptic terminals. In response to paired stimuli (separated by 150 ms), IPSCs in VB relay neurons show substantial paired-pulse depression. At all of the concentrations we tested (20–100 mM), ethanol had no effect on the paired-pulse ratio. In contrast, baclofen (5 μM), a GABAB receptor agonist that acts by decreasing GABA release from the presynaptic terminal, significantly increased the paired-pulse ratio from 0.59 ± 0.04 to 0.97 ± 0.17 (p < 0.05, n = 7). These results suggest that ethanol does not modulate synaptic GABA release in the thalamus.

Discussion

Alcohol is one of the most widely abused drugs. Blood alcohol levels between 5 and 20 mM reduce anxiety and produce mild sedation; these levels are commonly associated with light to moderate intoxication associated with social drinking. Blood ethanol (20–50 mM) typically elicits profound sedation, cognitive impairment, amnesia, and loss of motor coordination. Higher concentrations of ethanol (100 mM) in normal individuals cause general anesthesia, de-
increased ventilation, and risk of death (Deitrich and Harris, 1996; Little, 1999). All of these effects are less pronounced in chronic alcoholics, who routinely tolerate extraordinary high levels of the drug. Many of the pharmacological properties of ethanol are shared by drugs, such as the benzodiazepines and barbiturates, that have long been known to achieve their effects via regulation of the GABA<sub>А</sub>-Rs, and a large body of evidence implicates GABA<sub>А</sub>-Rs as an important target for ethanol in the CNS (Martz et al., 1983; Grobin et al., 1998). However, the mechanisms by which ethanol enhances GABAergic transmission are unclear and may vary substantially among brain regions (Weiner and Valenzuela, 2006).

The main findings of this study are as follows: i) Ethanol (50 mM), but not 20 mM ethanol, reduces firing rate of depolarized VB neurons via GABA<sub>А</sub>-Rs; ii) ethanol (≥50 mM) enhances tonic inhibition mediated by extrasynaptic GABA<sub>А</sub>-Rs; iii) ethanol (100 mM), but not 20 to 50 mM ethanol, exerts a postsynaptic action to prolong IPSCs on VB neurons; iv) enhancement of tonic currents by ethanol is absent in VB relay neurons from α<sub>4</sub> subunit knockout mice; and v) ethanol has no presynaptic action at inhibitory synapses made by reticular thalamic nucleus neurons on VB neurons.

In the present study, we demonstrate that ethanol (≥50 mM) does not change the amplitude or decay time of spontaneous IPSCs or evoked IPSCs in VB relay neurons. In contrast, 100 mM ethanol significantly prolongs both spontaneous IPSCs and evoked IPSCs. This finding is consistent with most previous studies on recombinant “synaptic” GABA<sub>А</sub>-Rs (α<sub>1</sub>β<sub>2</sub>γ<sub>2</sub> and α<sub>2</sub>β<sub>2</sub>γ<sub>2</sub> subtypes) heterologously expressed in cultured cells (Sigel et al., 1993; Mihić et al., 1997) and native synaptic GABA<sub>А</sub>-Rs in slices of different brain regions (Weiner and Valenzuela, 2006), which suggests that synaptic GABA<sub>А</sub>-Rs may not act as the direct target of ethanol at subanesthetic concentrations (≤50 mM).

An indirect action of ethanol on GABA<sub>А</sub>-Rs via presynaptic sites has been observed in many brain regions, including the amygdala (Roberto et al., 2003, 2004; Roberto and Siggins, 2006; Zhu and Lovinger, 2006), the cerebellum (Carta et al., 2004; Hanchar et al., 2005; Ming et al., 2006; Kelm et al., 2007), the hippocampus (Ariwodola and Weiner, 2004; Sanna et al., 2004; Galindo et al., 2005), and the nucleus accumbens (Nie et al., 2000; Crowder et al., 2002). However, we were unable to detect any change of spontaneous IPSC frequency or paired-pulse ratio of evoked IPSCs by ethanol (20–100 mM) in VB relay neurons, which suggests that presynaptic GABA release in the thalamus is insensitive to ethanol.

Recently, GABA<sub>А</sub>-Rs have been shown to be present at extrasynaptic sites as well as subsynaptic sites (Farrant and Nusser, 2005; Mody, 2005). Several groups have begun to look at the potential for alcohol action at extrasynaptic GABA<sub>А</sub>-Rs. First of all, two groups reported that recombinant α<sub>1</sub>β<sub>2</sub>δ (Sundström-Poromaa et al., 2002) and α<sub>2</sub>β<sub>2</sub>δ (Wallner et al., 2003) GABA<sub>А</sub>-Rs are extremely sensitive to alcohol, with enhancement of function noted at alcohol concentrations as low as 3 mM. However, the data in these two studies are inconsistent in terms of the dose-dependent ethanol response at extrasynaptic GABA<sub>А</sub>-Rs (Borghese et al., 2006; Yamashita et al., 2006). Enhancement of tonic currents mediated presumably by α<sub>4</sub>β<sub>6</sub>, α<sub>4</sub>β<sub>6</sub>, or α<sub>4</sub>β<sub>6</sub> GABA<sub>А</sub>-Rs has also been observed in hippocampal or cerebellar brain slices (Wei et al., 2004; Hanchar et al., 2005; Glykys et al., 2007). These alcohol effects on α<sub>4</sub>β<sub>6</sub> GABA<sub>А</sub>-Rs are further exaggerated by a mutation (R100Q) in the α<sub>4</sub> subunit of the GABA<sub>А</sub>-Rs (Hanchar et al., 2005). Contrasting observations on native extrasynaptic GABA<sub>А</sub>-Rs have been reported by other groups (Carta et al., 2004; Valenzuela et al., 2005; Borghese et al., 2006; Botta et al., 2007; Korpi et al., 2007). The reasons for these discrepancies are still elusive.

In thalamocortical relay neurons and dentate granule cells, α<sub>4</sub>β<sub>6</sub> GABA<sub>А</sub>-Rs have been shown to be located at extrasynaptic sites and to mediate tonic inhibition (Belelli et al., 2005; Jia et al., 2005; Chandra et al., 2006; Herd et al.,
2008). Small, but measurable, tonic currents have been recorded from β2 knockout mice (Belelli et al., 2005; Herd et al., 2008). The residual tonic currents suggest the possible contribution of the αβδ subtype or an unknown subunit compensation induced by gene knockout. Thalamic extrasynaptic GABA_A-Rs have also been implicated in the action of hypnotics and anesthetics (Belelli et al., 2005; Cope et al., 2005; Chandra et al., 2006; Jia et al., 2008a).

In this study, we found that tonic currents are not significantly enhanced by ethanol at low concentrations (10–30 mM) associated with social alcohol drinking. It seems that extrasynaptic GABA_A-Rs (mainly αβδ subtype) expressed in VB relay neurons are not as sensitive to ethanol as recombinant GABA_A-Rs expressed in X. laevis oocytes (Sundstrom-Poromaa et al., 2002; Wallner et al., 2003) or the extrasynaptic GABA_A-Rs of dentate granule cells (Wei et al., 2004). However, VB relay neurons are sensitive to sedative or anesthetic concentrations of ethanol (≥50 mM). At 50 mM, ethanol enhances tonic currents by approximately 50% and decreases the excitability of the relay neurons. The reasons for the discrepancies in this literature are still elusive. They may arise from methodological issues, for example, the differences in expression systems, tissue preparation, or recording temperatures, and one must also consider the possibility that ethanol might indirectly modulate the activity of extrasynaptic GABA_A-Rs. For example, ethanol might enhance tonic inhibition by stimulating the nonvesicular release of taurine (Olive, 2002), a potent agonist of these receptors (Jia et al., 2008b).

We have shown previously that gabazine, an antagonist of GABA_A-Rs, has little effect on the holding current in VB relay neurons from Gabra4−/− mice (Chandra et al., 2006), which is consistent with a loss of these extrasynaptic receptors. Likewise, 50 mM ethanol failed to evoke any significant current shift in VB neurons from Gabra4−/− mice (Chandra et al., 2006). At this concentration, ethanol does not change the properties of IPSCs from wild-type and Gabra4−/− mice either. Therefore, ethanol (≥50 mM) selectively enhances the activity of extrasynaptic GABA_A-Rs containing α4 subunits. Similar abolition of ethanol-induced tonic currents has also been shown in dentate gyrus neurons from Gabra4−/− mice (Liang et al., 2008).

Tonic inhibition mediated by extrasynaptic GABA_A-Rs plays a crucial role in regulating excitability at the level of individual neurons and within neuronal networks (Semyanov et al., 2004). In the present study, we show that the tonic firing in VB relay neurons was decreased by 50 mM ethanol but not by 20 mM. In addition, preapplied gabazine occluded the inhibition of tonic firing by 50 mM ethanol, which indicates that GABA_A-Rs are critical for the inhibitory effects of ethanol in the thalamus.

Alcohol not only has sedative effects that can promote onset of sleep but also causes abnormal sleep patterns (Kubota et al., 2002). After drinking alcohol, the time spent in deep (slow-wave) sleep is increased, whereas the time spent in the dreaming state (rapid eye movement sleep) is decreased. There can be little argument concerning the pivotal role of the thalamus in controlling the sleep-wake transition and in sensory transmission. The thalamocortical circuit represents an important potential target for alcohol, as reflected in the electroencephalogram changes that occur during drinking. A previous in vivo study demonstrates that 4,5,6,7-tetrahydroisoxazo[4,5-c]pyridin-3-ol, a hypnotic, works through extrasynaptic GABA_A-Rs that contain the 6 subunits (Winsky-Sommerer et al., 2007). Our results indicate that extrasynaptic GABA_A-Rs may also play a role in the action of sedative concentrations of ethanol (≥50 mM) in the thalamus. Given that sleep disturbances have been suggested to play a reciprocal role in the progression of alcoholism (Brower et al., 1998; Brower, 2001), the extrasynaptic GABA_A-Rs in the thalamus may be a potential therapeutic target for the treatment of alcoholism.

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