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Multiple Actions of Propofol on $\alpha\beta\gamma$ and $\alpha\beta\delta$ $GABA_A$ Receptors

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ABSTRACT

$GABA_A$ receptors are predominantly composed of $\alpha\beta\gamma$ and $\alpha\beta\delta$ isoforms in the brain. It has been proposed that $\alpha\beta\gamma$ receptors mediate phasic inhibition, whereas $\alpha\beta\delta$ receptors mediate tonic inhibition. Propofol (2,6-di-isopropylphenol), a widely used anesthetic drug, exerts its effect primarily by modulating $GABA_A$ receptors; however, the effects of propofol on the kinetic properties of $\alpha\beta\gamma$ and $\alpha\beta\delta$ receptors are uncertain. We transfected human embryonic kidney (HEK293T) cells with cDNAs encoding rat α1, α6, β3, γ2L, or δ subunits and performed whole-cell patch-clamp recordings to explore this issue. Propofol (3 μM) increased GABA concentration-response curve maximal currents similarly for both $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptors, but propofol increased those for $\alpha1\beta3\delta$ and $\alpha6\beta3\delta$ receptors differently, the increase being greater for $\alpha1\beta3\delta$ than for $\alpha6\beta3\delta$ receptors. Propofol (10 μM) produced similar alterations in $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptor currents when using a preapplication protocol; peak currents were not altered, desensitization was reduced, and deactivation was prolonged. Propofol enhanced peak currents for both $\alpha1\beta3\delta$ and $\alpha6\beta3\delta$ receptors, but the enhancement was greater for $\alpha1\beta3\delta$ receptors. Desensitization of these two isoforms was not modified by propofol. Propofol did not alter the deactivation rate of $\alpha1\beta3\delta$ receptor currents but did slow deactivation of $\alpha6\beta3\delta$ receptor currents. The findings that propofol reduced desensitization and prolonged deactivation of γ2L subunit-containing receptors and enhanced peak currents or prolonged deactivation of δ subunit-containing receptors suggest that propofol enhancement of both phasic and tonic inhibition may contribute to its anesthetic effect in the brain.

$GABA_A$ receptors are ligand-gated pentameric chloride ion channels and mediate the majority of inhibition in the central nervous system. More than 16 different $GABA_A$ receptor subunit subtypes have been identified, including α1 through α6, β1 through β3, γ1 through γ3, δ, ϵ, π, and θ (Olsen and Macdonald, 2002). McKernan and Whiting (1996) suggested that $GABA_A$ receptors may exist in vivo predominantly as $\alpha\beta\gamma$ and $\alpha\beta\delta$ isoforms. The $\alpha\beta\gamma$ isoforms are mainly localized in GABAergic synapses, but $\alpha\beta\delta$ isoforms were found on extra- or perisynaptic membranes (Nusser et al., 1998; Wei et al., 2003), suggesting that $\alpha\beta\gamma$ receptors may mediate phasic inhibition and $\alpha\beta\delta$ receptors may be involved in tonic inhibition (Bai et al., 2001; Stell et al., 2003). Recombinant $\alpha\beta\gamma$ receptors expressed in mammalian cells exhibited rapid desensitization (Haas and Macdonald, 1999; Bianchi and Macdonald, 2001; Scheller and Forman, 2002). However, α1 or α4 subunit-containing $\alpha\beta\delta$ $GABA_A$ receptors had relatively less desensitization (Brown et al., 2002; Wohlfarth et al., 2002; Feng et al., 2004), although α6 subunit-containing $\alpha\beta\delta$ receptors were more desensitizing (Bianchi et al., 2002).

Several widely used general anesthetic drugs, including propofol (2,6-di-isopropylphenol), exert their effects in the central nervous system mainly by enhancing $GABA_A$ receptor currents (Olsen and Macdonald, 2002). Modulation of $\alpha\beta\gamma$ receptor current amplitudes by propofol has been substantially explored (Hill-Venning et al., 1997; Uchida et al., 1997; Lam and Reynolds, 1998; Pistis et al., 1999; Carlson et al., 2000; Davies et al., 2001; Krasowski et al., 2001; Williams and Akabas, 2002), but propofol effects on the kinetic properties of recombinant $\alpha\beta\gamma$ receptors are unclear. Although one study suggested that propofol slightly enhanced the function of $\alpha4\beta3\delta$ receptors (Brown et al., 2002), its effects on current kinetics of other $\alpha\beta\delta$ isoforms are unknown. Therefore, modulation of propofol on recombinant $\alpha\beta\gamma$ and $\alpha\beta\delta$ receptors was examined to explore the potential effects of propofol on phasic and tonic GABAergic inhibition. $GABA_A$ receptor α1 subunit mRNA is ubiquitously expressed in the brain, whereas α6 subunit mRNA is restrictively found in the cerebellum (Wisden et al., 1992). In addition, α6 subunits

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ABBREVIATION: HEK, human embryonic kidney.

preferably coassemble with δ subunits, and the α6βδ receptor is one of the predominant δ subunit-containing $GABA_A$ receptor isoforms in the brain (Poltl et al., 2003). It is of interest to determine whether propofol has different effects on α1 and α6 subunit-containing $GABA_A$ receptors. Therefore, modulation of recombinant α1βγ, α6βγ, α1βδ, and α6βδ receptors by propofol was examined to explore the potential α subunit-dependent effects of propofol.

In the present study, we demonstrated subunit-specific propofol activation of γ2L and δ subunit-containing $GABA_A$ receptors. Propofol evoked a greater maximal conductance change (ΔG) from γ2L than from δ subunit-containing receptors. Propofol similarly decreased the desensitization and prolonged the deactivation of α1β3γ2L and α6β3γ2L receptors without affecting the peak current amplitudes. Although propofol modulation of αβγ $GABA_A$ receptor currents was relatively insensitive to the α subunit subtype, α subtype-specific effects of propofol were observed for αβδ receptors. Propofol produced a greater enhancement of peak current amplitudes for α1β3δ than for α6β3δ receptors and prolonged the deactivation of α6β3δ receptor currents without altering deactivation of α1β3δ receptor currents.

Materials and Methods

Expression of Recombinant $GABA_A$ Receptors in Human Embryonic Kidney Cells. HEK293T cells were grown in Dulbecco's modified Eagle's medium (Invitrogen, Carlsbad, CA) in an incubator at 37°C with 5% CO_2 and 95% air. The cells were seeded at a density of 400,000/dish in 60-mm culture dishes (Corning Incorporated, Corning, NY) and transfected the following day with the combinations of cDNAs encoding rat α1, α6, β3, γ2L, and δ $GABA_A$ receptor subunits (2 μg of each subunit in different ternary combinations) along with 2 μg of pHOOK (Invitrogen) using a modified calcium phosphate precipitation method (Fisher and Macdonald, 1997). The cells were incubated at 37°C for 4 h with 3% CO_2 and then shocked for 30 s with 15% glycerol (Sigma-Aldrich, St. Louis, MO). The selection marker pHOOK encoded a cell surface antibody (sFv) that bound to the antigen (phOx) coated on the ferromagnetic beads (Invitrogen). The bead-bound transfected cells were separated from nontransfected cells using a magnetic stand (Greenfield et al., 1997). Electrophysiological recordings were obtained 24 h later. Eighty two percent of cells that bound beads also expressed $GABA_A$ receptors (~80% for α1β3γ2L receptors, ~79% for α1β3δ receptors, 86% for α6β3γ2L receptors, and ~87% for α6β3δ receptors).

Whole-Cell Recordings. Whole-cell macroscopic currents were recorded using the patch-clamp technique at room temperature. The recording electrodes were pulled from the thin-wall borosilicate glass tubing (i.d., 1.12 mm; o.d., 1.5 mm) (World Precision Instruments Inc., Sarasota, FL) on a P-2000 Quartz Micropipette Puller (Sutter Instrument Company, Novato, CA). The electrodes were fire-polished on an MF-830 Microforge (Narishige, Tokyo, Japan), and the resistances of the electrodes were 0.9 to 1.6 MΩ when filled with an internal solution (see *Chemicals, Solutions, and Drug Application* for ionic composition).

Currents were recorded with an Axopatch 200A patch-clamp amplifier (Axon Instruments Inc., Union City, CA) and Digidata 1200 series interface (Axon Instruments Inc.). Series resistance was not compensated given that we previously reported that desensitization rate and extent were not affected by the current size we usually obtained from these recombinant $GABA_A$ receptors (Bianchi and Macdonald, 2002), suggesting that series resistance errors did not significantly affect our interpretations.

Chemicals, Solutions, and Drug Application. All chemicals were purchased from Sigma-Aldrich. The external bath solution was composed of 142 mM NaCl, 1 mM $CaCl_2$, 6 mM $MgCl_2$, 8 mM KCl, 10 mM glucose, and 10 mM HEPES (pH 7.4, 328–330 mOsm). The internal micropipette solution consisted of 153 mM KCl, 1 mM $MgCl_2$, 10 mM HEPES, 2 mM MgATP, and 5 mM EGTA (pH 7.3, 301–309 mOsm). This combination of the external and internal solutions produced an E_{CL} near 0 mV and an E_K at −75 mV.

GABA was dissolved in water, and propofol was dissolved in dimethyl sulfoxide to make 1 M stock solutions. The working solutions were prepared by diluting the stock solution with external solution on the day of the experiment. The maximal final concentration of dimethyl sulfoxide in working solutions was 0.3%. Drugs were applied by gravity using an ultrafast delivery device consisting of multibarrel tubes connected to a Perfusion Fast-Step system (Warner Instruments Inc., Hamden, CT). The 10 to 90% open electrode tip rise time of solution exchange was approximately 0.4 ms. Consecutive drug applications were separated by an interval of at least 45 s to minimize accumulation of desensitization. The duration of GABA or propofol application was 4 s.

Data Analysis. Whole-cell currents were analyzed offline using Clampfit 8.1 (Axon Instruments). Peak currents were measured manually from the baseline to the transient peak. Potentiation of GABA current by propofol (percentage of GABA current) was determined by dividing the peak current of coapplication of GABA and propofol by the peak current evoked by GABA alone and multiplying by 100. Normalized concentration-response data were fitted using a logistic equation with a variable slope: $I = I_{max}/(1 + 10^{(LogEC_{50} - Logdrug) \times n_H})$. I was the peak current evoked by a given concentration of GABA or GABA and propofol coapplication. I_{max} was the maximal peak current. EC_{50} was defined as the GABA concentration at which 50% of maximal response was evoked. Peak conductance change (ΔG) was calculated by dividing the peak current by the holding potential. The extent of desensitization (percent) was calculated by dividing the amount of current loss after 4 s of drug application by peak current and multiplying by 100. The deactivation current phase was analyzed by fitting using the standard exponential Levenberg-Marquardt methods, and the exponential components were expressed in the form of $\Sigma a_n \tau_n$, where a was the relative amplitude, τ was the time constant, and n (= 1 or 2) was the number of exponential components. A weighted τ was used to compare the rates of deactivation: $a_1 \times \tau_1/(a_1 + a_2) + a_2 \times \tau_2/(a_1 + a_2)$, where a_1 and a_2 were the relative amplitudes of the fast and slow exponential components (at time 0), and τ_1 and τ_2 were the corresponding time constants. Data were reported as mean ± S.E.M. Paired Student's t test was used to compare the changes before and after propofol treatment. Unpaired Student's t test was used to compare the alterations between different treatment groups. The difference was considered to be statistically significant if p was less than 0.05.

Results

GABA Sensitivity of γ2L and δ Subunit-Containing $GABA_A$ Receptors Assembled with Either an α1 or α6 Subunit. We first examined the GABA sensitivity of the four isoforms to be studied using standard concentration-response experiments. Whole-cell currents were recorded from recombinant α1β3γ2L, α6β3γ2L, α1β3δ, and α6β3δ $GABA_A$ receptors (Fig. 1, A–D). Cells were voltage-clamped at −20 mV for cells transfected with γ2L subunit-containing receptors, and because of the smaller amplitudes of αβδ currents, cells were voltage-clamped at −50 mV for cells transfected with δ subunit-containing receptors (Wohlfarth et al., 2002; Feng et al., 2004). $GABA_A$ receptor channel activation is not voltage-dependent at negative membrane potentials (−10 to −75 mV), although some reports show different degrees of nonlinearity (rectification) at positive potentials (Bianchi et al., 2002). In a recent report on pentobarbital modulation of

$\alpha1\beta3\delta$ and $\alpha1\beta3\gamma2L$ receptors (Feng et al., 2004), membrane potential was held at both −20 and −50 mV for each isoform, and pentobarbital-evoked effects were consistent for both receptor isoforms at both holding potentials. In addition, membrane potential was clamped from −10 to −75 mV to study neurosteroid modulation of these receptor isoforms, and no voltage-dependent effects were observed (Wohlfarth et al., 2002). As GABA concentrations were increased, the GABA-evoked whole-cell peak conductance change (ΔG) increased (Fig. 1E). The maximal ΔG for the $\alpha1\beta3\gamma2L$ isoform was 270.3 ± 47.6 nS ($n = 6$), which was not significantly different from that for $\alpha6\beta3\gamma2L$ receptors (206.9 ± 65.6 nS, $n = 7$) but was significantly greater than that for $\alpha6\beta3\delta$ (81.5 ± 25.3 nS, $n = 6$) ($p < 0.01$) and $\alpha1\beta3\delta$ (22.1 ± 11.1 nS, $n = 5$) ($p < 0.01$) receptors. The maximal ΔG evoked by GABA from $\alpha6\beta3\gamma2L$ receptors was not significantly different from that evoked from $\alpha6\beta3\delta$ receptors but was significantly greater than that from $\alpha1\beta3\delta$ receptors ($p < 0.05$). The maximal ΔG evoked by GABA from $\alpha6\beta3\delta$ receptors was not significantly different than that evoked from $\alpha1\beta3\delta$ receptors.

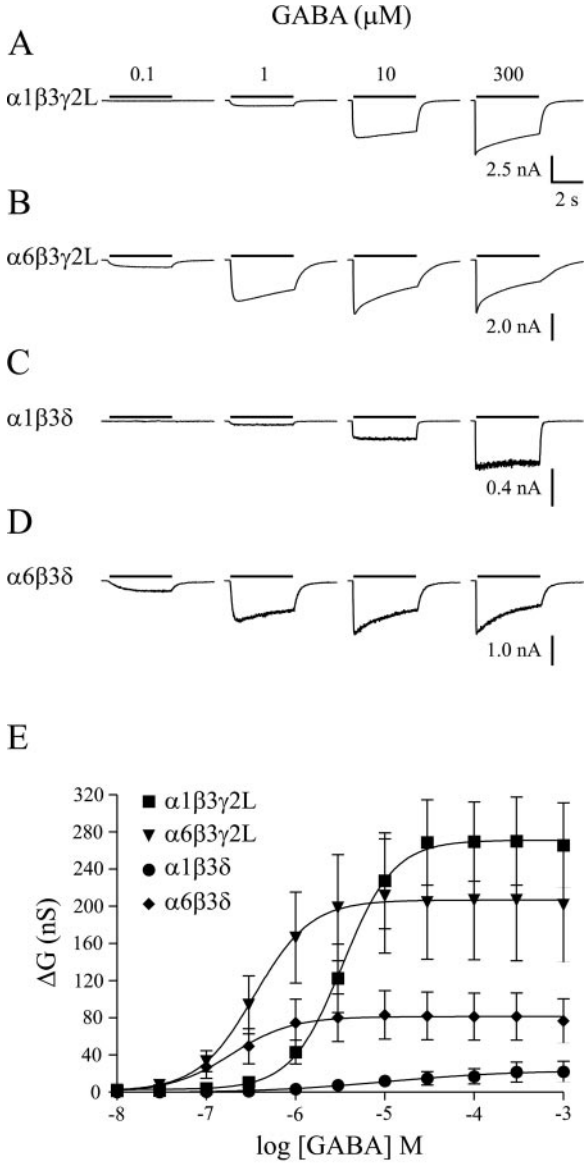

Fig. 1. GABA concentration-response patterns of $\alpha\beta\gamma2L$ and $\alpha\beta\delta$ $GABA_A$ receptors containing either an $\alpha1$ or $\alpha6$ subunit subtype. A–D, representative whole-cell current traces evoked by different concentrations of GABA from recombinant $\alpha1\beta3\gamma2L$, $\alpha6\beta3\gamma2L$, $\alpha1\beta3\delta$, and $\alpha6\beta3\delta$ $GABA_A$ receptors. E, GABA concentration-response curve expressed as mean peak conductance changes (ΔG) versus a series of GABA concentrations for $\alpha1\beta3\gamma2L$ ($n = 6$, ■), $\alpha6\beta3\gamma2L$ ($n = 7$, ▼), $\alpha1\beta3\delta$ ($n = 5$, ●), and $\alpha6\beta3\delta$ ($n = 6$, ◆) receptors. The solid line above each current trace represents the duration (4 s) of GABA application. The error bars represent means ± S.E.M.

As reported previously, $\alpha6$ subunit-containing $GABA_A$ receptors had a lower GABA EC_{50} than $\alpha1$ subunit-containing receptors (Saxena and Macdonald, 1996; Fisher et al., 1997). The EC_{50} for $\alpha6\beta3\gamma2L$ receptors (0.49 ± 0.14 μM) was smaller than that for $\alpha1\beta3\gamma2L$ receptors (6.17 ± 2.33 μM) ($p < 0.05$). The EC_{50} for $\alpha6\beta3\delta$ receptors (0.28 ± 0.05 μM) was also smaller than that for $\alpha1\beta3\delta$ receptors (5.24 ± 0.43 μM) ($p < 0.001$). No significant differences in EC_{50} values between $\alpha6\beta3\gamma2L$ and $\alpha6\beta3\delta$ receptors or $\alpha1\beta3\gamma2L$ and $\alpha1\beta3\delta$ receptors were observed (Fig. 1E). The mean Hill coefficients for $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptors were 1.6 ± 0.2 and 1.5 ± 0.1, respectively. The mean Hill coefficients for $\alpha1\beta3\delta$ and $\alpha6\beta3\delta$ receptors were 1.0 ± 0.1 and 1.3 ± 0.1, respectively.

Differences in Direct Activation of γ2L or δ Subunit-Containing $GABA_A$ Receptors by Propofol. Propofol has been reported to directly activate $GABA_A$ receptors (Orser et al., 1994; Lam and Reynolds, 1998; Pistis et al., 1999; Davies et al., 2001; Krasowski et al., 2001; Brown et al., 2002; Dong and Xu, 2002). Propofol directly activated both γ2L and δ subunit-containing $GABA_A$ receptors (Fig. 2, A–D). However, similar to the results obtained with GABA, propofol evoked a greater maximal ΔG from γ2L than from δ subunit-containing receptors regardless of whether an $\alpha1$ or $\alpha6$ subtype was present (Fig. 2E).

For both γ2L and δ subunit-containing $GABA_A$ receptors, propofol-evoked direct current showed no or minimal desensitization at propofol concentrations up to 300 μM. However, at very high concentrations (>1 mM), propofol currents were rapidly activating and showed extensive desensitization, and a "rebound" current appeared upon washout of propofol (Fig. 2, A–D). The increased desensitization and appearance of a rebound current might have resulted from propofol blocking open $GABA_A$ receptor channels at a low-affinity site (Adodra and Hales, 1995; Davies et al., 2001). It seemed that the rate of desensitization was faster and the extent of desensitization was larger for $\alpha6$ than for $\alpha1$ subunit-containing receptors. The mechanisms underlying this phenomenon remain unknown. One possibility may be that the affinity of propofol to the channel-binding site is greater for $\alpha6$ than for $\alpha1$ subunit-containing receptors, so that more complete block is observed in $\alpha6$ subunit-containing receptors. The multiphasic nature of the propofol concentration-response curve may also be partly explained by open channel block. However, the basis for the rapid change in current activation rate at high concentrations was unclear and was not further investigated.

Propofol Enhanced Peak Currents Evoked by a High Concentration of GABA from $\alpha1\beta3\delta$ More Than from $\alpha1\beta3\gamma2L$, $\alpha6\beta3\gamma2L$, and $\alpha6\beta3\delta$ $GABA_A$ Receptors. Performing concentration-response curves in the presence of a modulator such as propofol can provide an initial assessment of possible mechanisms of action by evaluating changes in EC_{50} and maximal current amplitudes. Propofol (3 μM) was coapplied with increasing GABA concentrations (from 0.01 to

1000 μM). Propofol slightly enhanced currents at high GABA concentrations and thus shifted the GABA concentration-response curve upward similarly (~115% of maximal current) for $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptors (Fig. 3, A–C). The GABA EC_{50} was not significantly altered by propofol for these receptor isoforms.

Coapplication of propofol with high concentrations of GABA evoked a greater current enhancement for $\alpha1\beta3\delta$ receptors than for $\alpha6\beta3\delta$ receptors (139.1 ± 4.9% versus 106.4 ± 2.6%) ($p < 0.001$) (Fig. 3, D–F). The maximal enhancement for $\alpha1\beta3\delta$ receptors was also significantly greater than that for $\alpha1\beta3\gamma2L$ ($p < 0.01$) and $\alpha6\beta3\gamma2L$ ($p < 0.05$) receptors. The EC_{50} for $\alpha1\beta3\delta$ receptors for GABA coapplied with propofol (7.05 ± 0.65 μM) was greater than that for GABA alone (5.24 ± 0.43 μM) ($p = 0.05$). The EC_{50} for $\alpha6\beta3\delta$ receptors was unchanged by propofol (Fig. 3F). The actual amount of enhancement of $GABA_A$ receptor current by propofol is somewhat difficult to interpret because the enhancement of $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptor currents is probably increased by the direct activation of propofol on these recep-

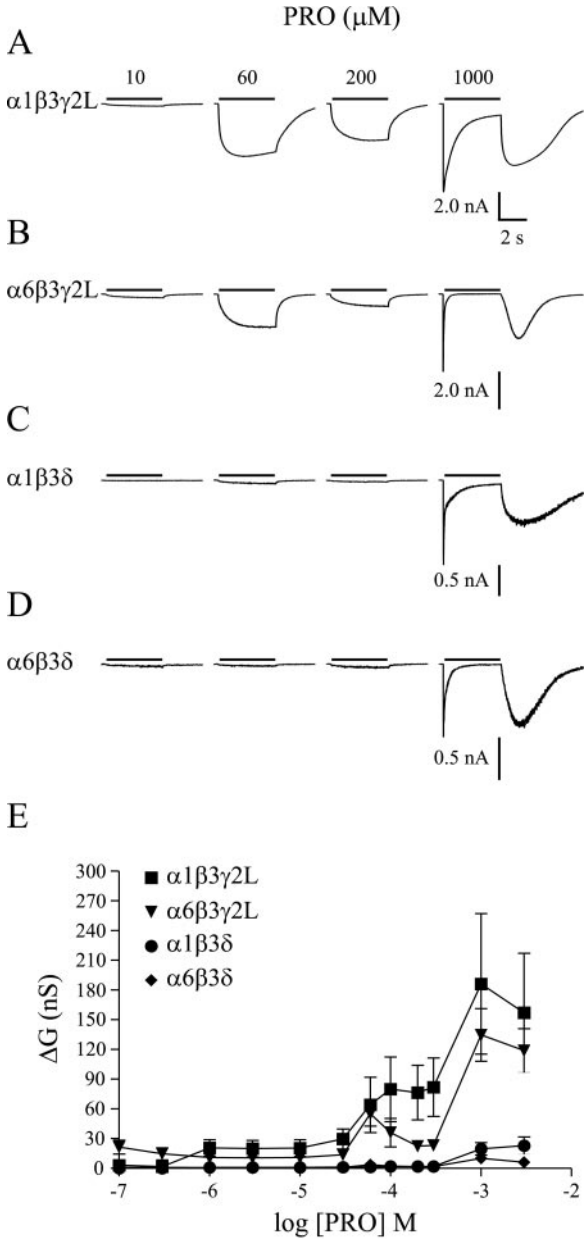

Fig. 2. Propofol evoked greater direct response from $\gamma2L$ than δ subunit-containing $GABA_A$ receptors. A–D, representative whole-cell current traces evoked by different concentrations of propofol from recombinant $\alpha1\beta3\gamma2L$, $\alpha6\beta3\gamma2L$, $\alpha1\beta3\delta$, and $\alpha6\beta3\delta$ $GABA_A$ receptors. E, propofol concentration-response curve expressed as mean peak conductance changes (ΔG) versus a series of propofol concentrations for $\alpha1\beta3\gamma2L$ (n = 6, ■), $\alpha6\beta3\gamma2L$ (n = 6, ▼), $\alpha1\beta3\delta$ (n = 7, ●), and $\alpha6\beta3\delta$ (n = 5, ◆) receptors. The solid line above each current trace represents the duration (4 s) of propofol application. The error bars represent means ± S.E.M.

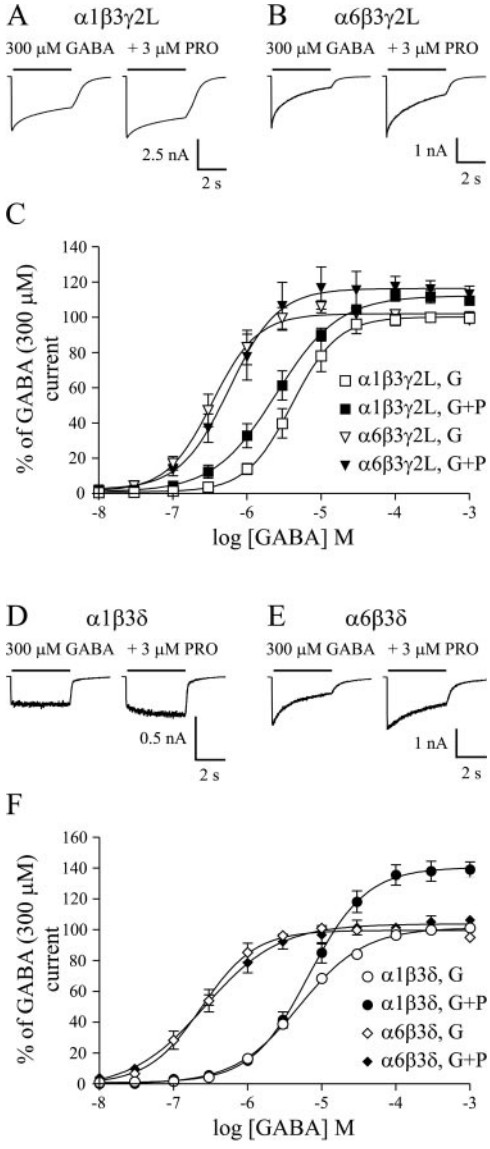

Fig. 3. Propofol produced greater enhancement of $\alpha1\beta3\delta$ receptor than $\alpha1\beta3\gamma2L$, $\alpha6\beta3\gamma2L$, and $\alpha6\beta3\delta$ receptor currents at high GABA concentrations. A and B, examples of whole-cell current traces evoked by GABA alone as well as coapplication of GABA and propofol (3 μM) from $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptors. C, concentration-response curves for GABA alone (open symbols) and coapplication of GABA with 3 μM propofol (solid symbols) plotted for $\alpha1\beta3\gamma2L$ (squares) and $\alpha6\beta3\gamma2L$ (triangles) receptors. D and E, examples of whole-cell current traces evoked by GABA alone as well as coapplication of GABA and propofol (3 μM) from $\alpha1\beta3\delta$ and $\alpha6\beta3\delta$ receptors. F, concentration-response curves for GABA alone (open symbols) and coapplication of GABA with 3 μM propofol (solid symbols) plotted for $\alpha1\beta3\delta$ (circles) and $\alpha6\beta3\delta$ (diamonds) receptors. The solid line above each current trace represents the duration (4 s) of GABA application or GABA and propofol coapplication. n = 5 to 7 cells for each GABA or GABA + propofol concentration-response curve. The error bars represent means ± S.E.M.

tors. Nonetheless, these concentration-response curves give the GABA concentration dependence in the presence or absence of propofol and therefore are functionally useful.

Modulation by Propofol of Peak Currents, Desensitization, and Deactivation Evoked by a Saturating Concentration of GABA Was Similar for $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ $GABA_A$ Receptors. We were interested in exploring the modulation by propofol of peak $GABA_A$ receptor currents and kinetic properties evoked by a saturating GABA concentration. Long pulses of 1 mM GABA provide information about multiple phases of desensitization as well as the deactivation after washout of GABA. To better resolve the fast phase of desensitization, the cells were lifted from the recording dish to improve solution exchange rate. Propofol (10 μM) was preapplied and followed by coapplication of propofol (10 μM) and a saturating GABA concentration (1 mM), allowing controlled duration of pre-equilibration as well as resolution of the direct effect of propofol. Propofol did not potentiate the peak GABA-evoked current of either $\alpha1\beta3\gamma2L$ (98.3 $\pm$ 1.4%, $n = 6$) or $\alpha6\beta3\gamma2L$ (97.4 $\pm$ 4.7%, $n = 6$) receptors (Fig. 4, A–C).

Mean desensitization of $\alpha1\beta3\gamma2L$ receptor current induced by GABA alone was 54.5 $\pm$ 5.0%, which was significantly smaller than that of $\alpha6\beta3\gamma2L$ receptor current (81.9 $\pm$ 3.1%) ($p < 0.001$). Propofol reduced the extent of desensitization for both $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptor currents. Mean desensitization was significantly reduced to 44.0 $\pm$ 5.6% ($p < 0.01$) for $\alpha1\beta3\gamma2L$ receptors and to 72.1 $\pm$ 3.9% ($p < 0.01$) for $\alpha6\beta3\gamma2L$ receptors (Fig. 4, A, B, and D). These results were consistent with prior studies of propofol on neuronal $GABA_A$ receptors (Bai et al., 1999; Dong and Xu, 2002).

Propofol also prolonged deactivation of both $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptor currents. The mean weighted deactivation rate for $\alpha1\beta3\gamma2L$ receptor currents was significantly increased from 420.6 $\pm$ 63.2 to 534.6 $\pm$ 76.1 ms by propofol ($p < 0.01$), and that of $\alpha6\beta3\gamma2L$ receptor currents was significantly increased from 346.3 $\pm$ 32.8 to 533.2 $\pm$ 68.6 ms ($p < 0.05$) (Fig. 4, A, B, and E).

Modulation by Propofol of Peak Currents and Deactivation with a Saturating Concentration of GABA Was Different for $\alpha1\beta3\delta$ and $\alpha6\beta3\delta$ $GABA_A$ Receptors. The preapplication and lifted cell techniques were also used to explore propofol modulation of peak currents and kinetic properties of $\alpha1\beta3\delta$ and $\alpha6\beta3\delta$ receptor currents. The mean peak current enhancement of $\alpha1\beta3\delta$ receptors by propofol (205.8 $\pm$ 33.1%, $n = 7$) was significantly greater than that of $\alpha6\beta3\delta$ receptors (107.6 $\pm$ 5.0%, $n = 7$) ($p < 0.05$) (Fig. 5, A–C).

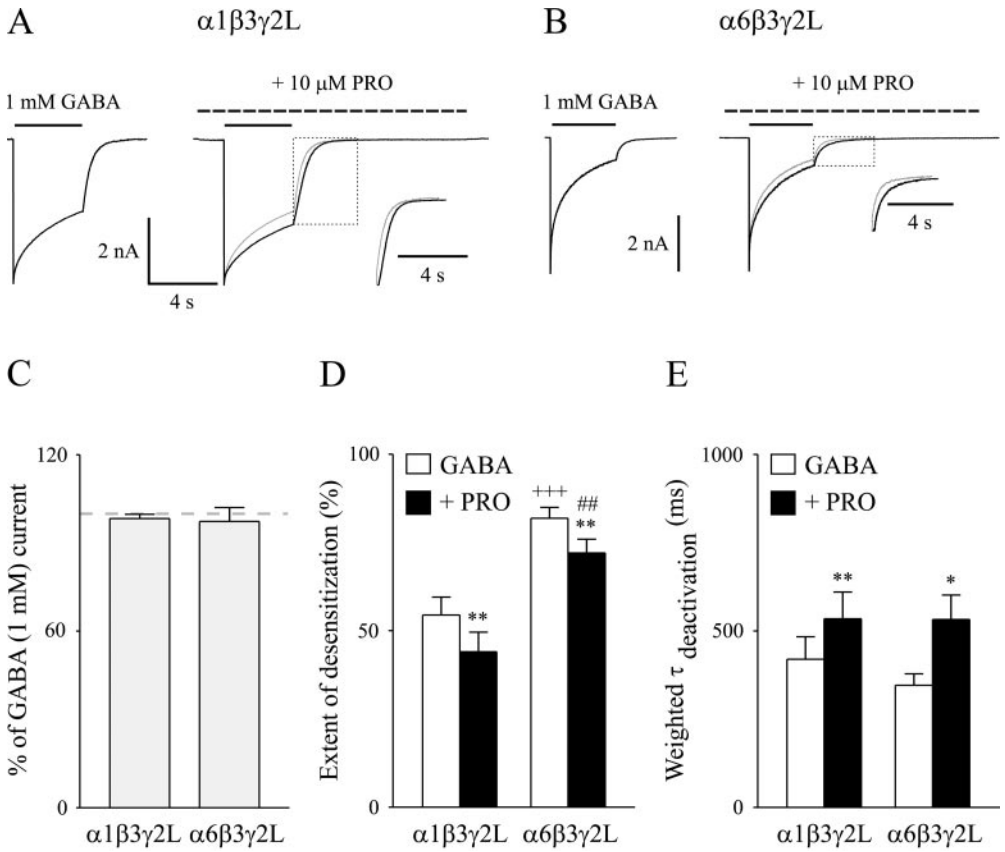

Fig. 4. Propofol modulated the peak current, desensitization, and deactivation of $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptors similarly. A and B, representative whole-cell current traces evoked by GABA (1 mM) alone as well as coapplication of GABA (1 mM) and propofol (10 μM) with propofol preapplied from $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptors. The GABA control current (gray trace) was normalized to the current evoked by coapplication of GABA and propofol to demonstrate the changes in desensitization and deactivation. C, propofol did not potentiate the mean GABA peak currents of $\alpha1\beta3\gamma2L$ ($n = 6$) and $\alpha6\beta3\gamma2L$ ($n = 6$) receptors. The gray dashed line indicates 100%. D, propofol treatment significantly decreased the mean desensitization of $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptors. E, propofol treatment significantly increased the mean time constant of deactivation of $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptors. The solid line above each representative current trace denotes the duration of GABA application, and the black dashed line denotes that of propofol application. The error bars represent means $\pm$ S.E.M. $*$, significantly different from corresponding GABA control at $p < 0.05$; $**$, $p < 0.01$; ##, significantly different from GABA + propofol of $\alpha1\beta3\gamma2L$ isoform at $p < 0.01$; and $+++$, significantly different from GABA control of $\alpha1\beta3\gamma2L$ isoform at $p < 0.001$.

Mean desensitization of $\alpha1\beta3\delta$ receptor currents for GABA alone was 8.9 ± 3.5%, which was significantly smaller than that for $\alpha6\beta3\delta$ receptor currents (49.3 ± 5.2%) ($p < 0.001$) (Fig. 5, A, B, and D), consistent with previous reports (Bianchi et al., 2002). Propofol did not alter the extent of desensitization for either isoform.

The deactivation rate of $\alpha1\beta3\delta$ receptor currents after application of GABA alone was 103.9 ± 16.0 ms, which was significantly faster than that for $\alpha6\beta3\delta$ receptor currents (315.0 ± 23.8 ms) ($p < 0.001$) (Fig. 5, A, B, and E). Although propofol did not alter deactivation of $\alpha1\beta3\delta$ receptor currents, it increased the deactivation rate to 411.5 ± 44.3 ms for $\alpha6\beta3\delta$ receptor currents ($p < 0.05$).

Discussion

The Enhancement of Maximal Peak Currents by Propofol Was Greater for $\alpha1\beta3\delta$ Receptors Than for $\alpha1\beta3\gamma2L$, $\alpha6\beta3\gamma2L$, and $\alpha6\beta3\delta$ Receptors. For all recombinant $GABA_A$ receptor isoforms examined in the present study, propofol directly activated the receptors with multiphasic concentration-response curves. The mechanisms underlying these properties remain unknown. One possibility is that there are multiple receptor binding sites with different affinities for propofol. Propofol in the presence of high GABA concentrations produced a more substantial upward shift of the GABA concentration-response curve for $\alpha1\beta3\delta$ than for $\alpha1\beta3\gamma2L$, $\alpha6\beta3\gamma2L$, and $\alpha6\beta3\delta$ receptors. Thus, propofol was similar to pentobarbital and neurosteroids in exerting greater potentiation of this receptor isoform (Wohlfarth et al., 2002; Feng et al., 2004). Coapplication of 3 μM propofol with high concentrations of GABA produced a small enhancement of $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptor currents. A part of the enhancement might be contributed by direct activation by propofol of $GABA_A$ receptors because propofol at this concentration evoked direct currents from $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptors. Consistent with this interpretation, when propofol was preapplied, and thus the direct activation current could be taken into account, $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptor peak currents were not increased by propofol. Thus, propofol modulation was similar to those of pentobarbital and neurosteroids (Wohlfarth et al., 2002; Feng et al., 2004), which did not potentiate maximal GABA-evoked $\alpha\beta\gamma$ currents. In contrast, propofol enhanced both $\alpha1\beta3\delta$ and $\alpha6\beta3\delta$ receptor peak currents. δ subunit-containing $GABA_A$ receptors have been reported to be modulated by a variety of structurally different compounds (Lees and Edwards, 1998; Thompson et al., 2002; Wohlfarth et al., 2002; Wallner et al., 2003; Feng et al., 2004). The consistent observation with δ subunit-containing receptors is that, unlike most $\alpha\beta\gamma$ isoforms, the maximal currents evoked by GABA can be in-

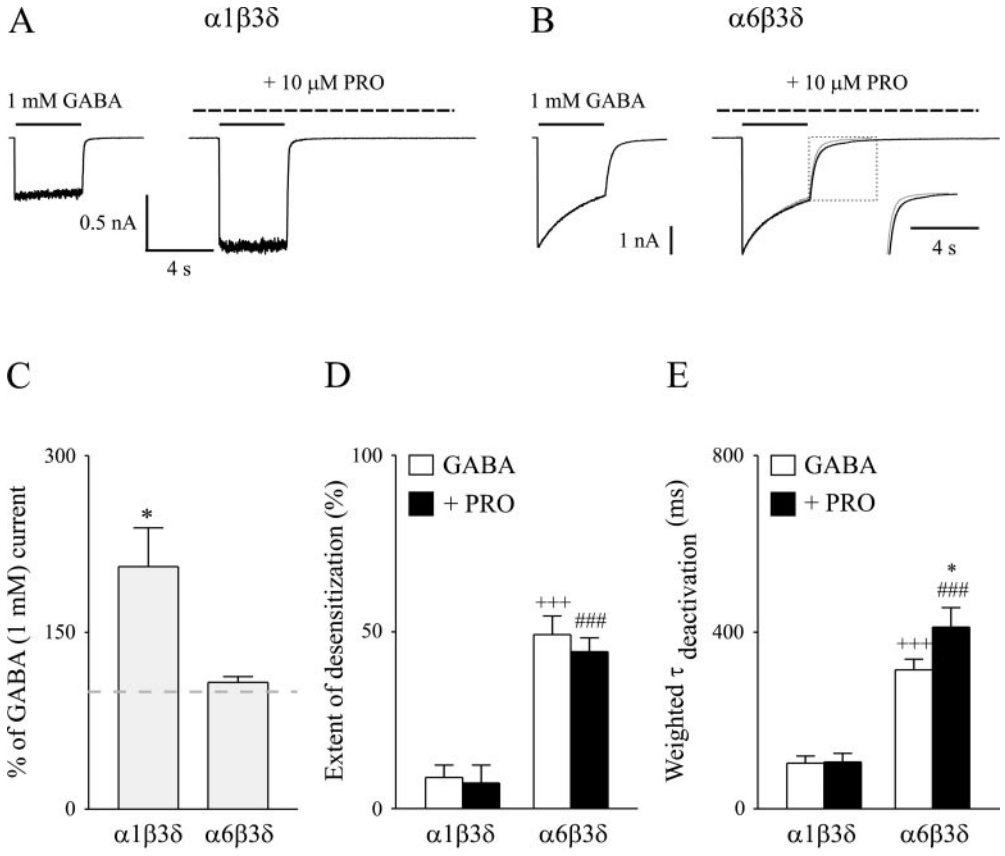

Fig. 5. Propofol differentially modulated the peak current and deactivation of $\alpha1\beta3\delta$ and $\alpha6\beta3\delta$ receptors. A and B, representative whole-cell current traces evoked by GABA (1 mM) alone as well as coapplication of GABA (1 mM) and propofol (10 μM) with propofol preapplied from $\alpha1\beta3\delta$ and $\alpha6\beta3\delta$ receptors. C, propofol produced significantly greater mean enhancement from $\alpha1\beta3\delta$ ($n = 7$) than from $\alpha6\beta3\delta$ ($n = 7$) receptors. The gray dashed line indicates 100%. D, propofol treatment did not significantly affect the mean desensitization of $\alpha1\beta3\delta$ and $\alpha6\beta3\delta$ receptors. E, propofol treatment significantly increased the mean time constant of deactivation of $\alpha6\beta3\delta$ receptors but did not alter that of $\alpha1\beta3\delta$ receptors. The solid line above each representative current trace denotes the duration of GABA application, and the black dashed line denotes that of propofol application. The error bars represent means ± S.E.M. *, significantly different from corresponding $\alpha6\beta3\delta$ GABA control or $\alpha6\beta3\delta$ isoform at $p < 0.05$; ###, significantly different from GABA + propofol of $\alpha1\beta3\delta$ isoform at $p < 0.001$; and +++, significantly different from GABA control of $\alpha1\beta3\delta$ isoform at $p < 0.001$.

creased by allosteric modulators. These observations are reminiscent of the increased efficacy of positive modulators on $\alpha\beta\gamma$ receptor currents activated by partial agonists. There is also direct evidence that GABA is not a "full" agonist at $\alpha\beta\delta$ isoforms, because the synthetic GABA analog 4,5,6,7-tetrahydroisoxazolo[4,5-*c*]pyridin-3-ol activated larger currents than GABA (Adkins et al., 2001; Brown et al., 2002). These data support the idea that GABA may be a partial agonist for δ subunit-containing $GABA_A$ receptors (Bianchi and Macdonald, 2003). It is noteworthy that propofol was reported to slightly enhance the saturating GABA-evoked peak currents of $GABA_A$ receptors on native hippocampal neurons (Bai et al., 1999), but the contribution of δ subunit-containing receptors on these neurons was not known (Wisden et al., 1992).

Subunit-Dependent Modulation of Recombinant $GABA_A$ Receptor Kinetic Properties by Propofol. Propofol significantly decreased the extent of desensitization and prolonged the deactivation of $\alpha1\beta3\gamma2L$ and $\alpha6\beta3\gamma2L$ receptors in a similar manner, suggesting that the kinetic modifications induced by propofol are predominantly dependent on the $\gamma2L$ rather than the α subunit in these receptors. This finding is consistent with a report on the modulation of $GABA_A$ receptor kinetic properties by propofol in native hippocampal neurons (Bai et al., 1999), because the predominant $GABA_A$ receptor isoform is $\alpha\beta\gamma2L$ in hippocampal pyramidal cells (Wisden et al., 1992). Similar alterations in kinetic properties produced by propofol were also reported for $GABA_A$ receptors in native spinal cord neurons (Dong and Xu, 2002), implying that $\alpha\beta\gamma2L$ receptors may also be predominantly present on these neurons. Although propofol decreased desensitization of $\gamma2L$ subunit-containing receptors, we observed prolonged current deactivation. If the decreased macroscopic desensitization reflected reduced stability of desensitized states, faster deactivation would be predicted based on the proposal that prolongation of deactivation is "coupled" with increased desensitization (Jones and Westbrook, 1995; Haas and Macdonald, 1999). A similar pattern of modulation was observed for pentobarbital modulation of $\alpha1\beta3\gamma2L$ receptor currents (Feng et al., 2004). We and others have recently suggested that increasing gating efficacy can secondarily decrease macroscopic desensitization as well as prolong deactivation (Bianchi and Macdonald, 2001; Scheller and Forman, 2002). Consistent with this mechanism, increased gating efficacy (frequency) was reported for propofol modulation of single $GABA_A$ receptor channels from neurons (Orser et al., 1994). Simulation studies also suggested that propofol-evoked prolongation of GABA current deactivation and reduced desensitization might be achieved by propofol stabilization of the ligand-bound pre-open state (Bai et al., 1999).

Propofol did not significantly affect desensitization but differentially modified the deactivation of $\alpha1\beta3\delta$ and $\alpha6\beta3\delta$ receptor currents, providing an additional example of independent modulation of desensitization and deactivation. Pentobarbital and neurosteroids have been reported to increase desensitization and prolong deactivation of $\alpha1\beta3\delta$ receptor currents (Wohlfarth et al., 2002; Feng et al., 2004). However, propofol did not significantly alter the desensitization and deactivation of $\alpha1\beta3\delta$ receptors in the present study, which is unexpected because any kinetic parameter that could increase maximal open probability of a nondesensitizing receptor should also prolong deactivation. We do not have an explanation for this observation. It is possible that we could not resolve changes in deactivation at the whole-cell level. The possible mechanism underlying the different effect of propofol and pentobarbital or neurosteroids on $\alpha1\beta3\delta$ receptor desensitization might be that these general anesthetics differentially modulated the rate constants of the $\alpha1\beta3\delta$ receptor desensitized state. Consistent with this possibility, these drugs had different effects on channel open states. Pentobarbital was reported to increase mean open duration of recombinant receptor single channel currents, including $\alpha1\beta3\delta$ receptors (Feng et al., 2004), whereas in contrast, propofol has been reported to increase channel open frequency (Orser et al., 1994). Propofol did not significantly modify desensitization of $\alpha6\beta3\delta$ receptor currents but significantly prolonged deactivation. The mechanisms for this propofol effect remain unclear. One parsimonious explanation may be that propofol slowed the agonist unbinding, which has been reported for another anesthetic drug, halothane (Li and Pearce, 2000). These data suggest that modulation by propofol of $GABA_A$ receptor kinetic properties is subunit-dependent.

Implications for Propofol Actions on $\gamma2L$ or δ Subunit-Containing Receptor Currents: Multiple Anesthetic Mechanisms. General anesthetics exert their effect in the brain largely by modulating $GABA_A$ receptor synaptic currents (Olsen and Macdonald, 2002). However, substantial recent evidence suggests that nonsynaptic or tonic forms of inhibition can have profound effects on neuronal excitability. Pentobarbital and several other general anesthetics have been reported to potentiate the currents of δ subunit-containing $GABA_A$ receptors (Lees and Edwards, 1998; Brown et al., 2002; Wohlfarth et al., 2002; Feng et al., 2004). These and the present studies suggest that δ subunit-containing receptors are an important target for general anesthetics. δ subunit-containing $GABA_A$ receptors are involved in tonic inhibition (Stell et al., 2003; Wei et al., 2003), suggesting that general anesthetics may partly exert their effect by enhancing tonic inhibition. This may be one explanation for the findings that the tonic inhibition was enhanced by propofol in hippocampal neurons (Bai et al., 2001; Bieda and MacIver, 2004). In addition,propofol as well as pentobarbital (Feng et al., 2004) decreased the desensitization and prolonged the deactivation of $\gamma2L$ subunit-containing receptors, which may mediate the phasic inhibition. This modification of kinetic properties by propofol has been demonstrated to prolong the synaptic currents (Bai et al., 1999). Therefore, some general anesthetics such as propofol may also exert their effect by enhancing phasic inhibition. In addition, it was reported that a clinically relevant concentration of propofol is 0.4 μM (Dong and Xu, 2002). It is noteworthy that propofol at this concentration evoked direct currents from $\gamma2L$ subunit-containing receptors. Thus, in addition to modulating $GABA_A$ receptor currents, propofol may directly activate $GABA_A$ receptors to contribute to its anesthetic effects in the brain.

The $\alpha1\beta\gamma2L$ receptor isoform is ubiquitously distributed in the brain and may be one of the major targets for propofol anesthetic effects. In contrast, $\alpha6\beta\gamma2L$ and $\alpha6\beta\delta$ isoforms are restricted to the cerebellum (Wisden et al., 1992), a structure that may be involved in propofol anesthetic side effects such as ataxia. In the present study, we report that propofol substantially enhanced $\alpha1\beta3\delta$ receptor peak currents; however, a previous study suggested $\alpha1\beta\delta$ receptors may be a minor

isoform of δ subunit-containing $GABA_A$ receptors in the brain (Poltl et al., 2003). Therefore, it is likely that $\alpha1\beta3\delta$ receptors have limited contribution to propofol effects in the brain. More importantly, the present findings that propofol similarly modulated the deactivation and/or desensitization of $\alpha1\beta3\gamma2L$, $\alpha6\beta3\gamma2L$, and $\alpha6\beta3\delta$ receptors suggest that propofol may exert similar effect on GABAergic inhibition in different regions of the brain. These data also suggest that the enhancement of tonic inhibition and phasic inhibition may be equally important for propofol anesthetic effects as well as side effects. Further experiments are needed to confirm these speculations in vivo.

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