

Pentobarbital Differentially Modulates $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ GABA_A Receptor Currents

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ABSTRACT

GABA_A receptors are modulated by a variety of compounds, including the neurosteroids and barbiturates. Although the effects of barbiturates on $\alpha\beta\gamma$ isoforms, thought to dominate phasic (synaptic) GABAergic inhibition, have been extensively studied, the effects of pentobarbital on kinetic properties of $\alpha\beta\delta$ GABA_A receptors, thought to mediate tonic (extra- or perisynaptic) inhibition, are unknown. Using ultrafast drug delivery and single channel recording techniques, we demonstrate isoform-specific pentobarbital modulation of low-efficacy, minimally desensitizing $\alpha 1\beta 3\delta$ currents and high-efficacy, rapidly desensitizing $\alpha 1\beta 3\gamma 2L$ currents. Specifically, with saturating concentrations of GABA, pentobarbital substantially potentiated peak $\alpha 1\beta 3\delta$ receptor currents but failed to potentiate peak $\alpha 1\beta 3\gamma 2L$ receptor currents. Also,

pentobarbital had opposite effects on the desensitization of $\alpha 1\beta 3\delta$ (increased) and $\alpha 1\beta 3\gamma 2L$ (decreased) receptor currents evoked by saturating GABA. Pentobarbital increased steady-state $\alpha 1\beta 3\delta$ receptor single channel open duration primarily by introducing a longer duration open state, whereas for $\alpha 1\beta 3\gamma 2L$ receptor channels, pentobarbital increased mean open duration by increasing the proportion and duration of the longest open state. The data support previous suggestions that GABA may be a partial agonist at $\alpha\beta\delta$ isoforms, which may render them particularly sensitive to allosteric modulation. The remarkable increase in gating efficacy of $\alpha 1\beta 3\delta$ receptors suggests that $\alpha\beta\delta$ isoforms, and by inference tonic forms of inhibition, may be important targets for barbiturates.

GABA_A receptors are ligand-gated chloride channels composed of five subunits with multiple subtypes, including $\alpha 1$ to $\alpha 6$, $\beta 1$ to $\beta 4$, $\gamma 1$ to $\gamma 3$, δ , ϵ , π , and θ (Olsen and Macdonald, 2002). The function of GABA_A receptor channels is allosterically modulated by many structurally different compounds such as neurosteroids, benzodiazepines, and barbiturates (Rupprecht and Holsboer, 1999; Olsen and Macdonald, 2002). The modulatory effects of these drugs are subunit selective in some cases (Pritchett et al., 1989; Thompson et al., 2002; Wallner et al., 2003). For example, neurosteroids significantly increased the maximal peak current amplitude and extent of desensitization of GABA_A receptors containing a δ subunit, but these kinetic responses were not observed for receptors containing a $\gamma 2L$ subunit (Wohlfarth et al., 2002).

Pentobarbital is an anesthetic barbiturate and exerts its CNS effects by interacting with GABA_A receptors (Olsen and Macdonald, 2002). At low concentrations, pentobarbital potentiates GABA_A receptor currents (Nicoll and Wojtowicz,

1980; Schulz and Macdonald, 1981) by increasing the proportion of longer single channel openings and thus increasing mean open duration. At higher concentrations, pentobarbital directly activates GABA_A receptors (Nicoll and Wojtowicz, 1980; Schulz and Macdonald, 1981; Krampfl et al., 2002). At millimolar concentrations, pentobarbital inhibits GABA_A receptor function, probably through a low-affinity open channel block mechanism (Akaike et al., 1987; Rho et al., 1996; Akk and Steinbach, 2000). These properties of pentobarbital (positive allosteric modulation, direct agonism, and open channel block) are similar to those reported for certain neurosteroids (Lambert et al., 1995; Rupprecht and Holsboer, 1999).

Although the effects of barbiturates on $\alpha\beta\gamma$ currents, thought to dominate phasic (synaptic) GABAergic inhibition, have been extensively studied, the modulatory effects of pentobarbital on the kinetic properties of $\alpha\beta\delta$ GABA_A receptors are still unknown. There is increasing evidence that $\alpha\beta\delta$ receptors may be selectively targeted to extra- or perisynaptic membranes, where they are thought to mediate tonic neuronal inhibition by responding to fluctuating concentrations of extracellular neurotransmitters such as GABA (Nusser et al., 1998; Bai et al., 2001; Stell et al., 2003; Wei et al., 2003). Recent studies have suggested that pentobarbital plays an important role in modulation of δ subunit-

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ABBREVIATIONS: CNS, central nervous system; HEK, human embryonic kidney; BES, *N,N*-bis[2-hydroxyethyl]-2-aminoethanesulfonic acid.

containing GABA_A receptors. Chronic pentobarbital treatment evoked an alteration of GABA_A receptor δ subunit mRNA in the CNS (Lin and Wang, 1996), and pentobarbital potentiated the response of δ subunit-containing GABA_A receptors (Adkins et al., 2001; Brown et al., 2002). In the present study, we transfected cDNAs encoding rat $\alpha 1$, $\beta 3$, and δ or $\alpha 1$, $\beta 3$, and $\gamma 2L$ GABA_A receptor subunits into human embryonic kidney (HEK 293T) cells and used ultrafast drug delivery and outside-out patch single channel recording techniques to characterize the distinct effects of pentobarbital on GABA_A receptors containing δ or $\gamma 2L$ subunits.

Materials and Methods

Cell Culture and Recombinant GABA_A Receptor Expression. HEK 293T cells (a gift from Dr. P. Connely, COR Therapeutics, San Francisco, CA) were maintained in Dulbecco's modified Eagle's medium (Invitrogen, Carlsbad, CA) supplemented with 10% fetal bovine serum (Invitrogen), 100 IU/ml penicillin, and 100 μ g/ml streptomycin (Invitrogen). HEK cells were grown in 10-cm culture dishes (Corning Glassworks, Corning, NY) in an incubator at 37°C with 5% CO₂ and 95% air. The cells were passaged at 3- to 4-day intervals using trypsin-EDTA (Invitrogen). One day before transfection, the cells were seeded at a density of 400,000/dish in 60-mm culture dishes (Corning Glassworks). Cells were transfected with cDNAs encoding rat $\alpha 1$, $\beta 3$, and δ or $\alpha 1$, $\beta 3$, and $\gamma 2L$ GABA_A receptor subunits using a modified calcium phosphate precipitation method (Fisher and Macdonald, 1997a). For each transfection, 2 μ g of each subunit cDNA along with 2 μ g of pHOOK (Invitrogen) were used. The cells were incubated for 4 h with 3% CO₂ and shocked thereafter for 30 s with 15% glycerol in BES-buffered saline (280 mM NaCl, 1.5 mM Na₂HPO₄·7H₂O, 50 mM BES). After continuous incubation with 5% CO₂ for 24 h, the cells were collected, and the transfected cells were selected using an immunomagnetic bead separation method (Greenfield et al., 1997). The selected cells were replated on 35-mm culture dishes (Corning Glassworks) for whole cell and single channel recordings 24 h later. The percentage of cells that both bound beads and expressed GABA_A receptors was 86% (118/137).

Whole Cell and Single Channel Recordings. Whole cell macroscopic currents were obtained with the cell attached to the dish (whole cell recording) or after lifting of the cells (lifted cell recording). Single channel microscopic currents were recorded from excised outside-out patches. Recording electrodes were pulled on a P-87 Flaming Brown micropipette puller (Sutter Instrument Company, Rafael, CA). The whole cell and lifted cell recording electrodes were pulled from the thin-wall borosilicate glass tubing (i.d. 1.12 mm, o.d. 1.5 mm) (WPI, Sarasota, FL) with resistances between 0.8 to 2 M Ω , and the single channel recording electrodes were pulled from the thick-wall borosilicate glass tubing (i.d. 0.84 mm, o.d. 1.5 mm) (WPI) with resistances between 6 to 16 M Ω . All electrodes were fire polished on an MF-9 Microforge (Narishige, Tokyo, Japan). The single channel recording electrodes were coated with polystyrene Q-dope (GC Electronics, Rockford, IL) after fire polishing to minimize the noise during recording.

Currents were recorded with either an Axopatch 1D or 200A patch-clamp amplifier (Axon Instruments, Foster City, CA) and Digidata 1200 series interface (Axon Instruments). The data were stored on a PC computer hard drive for offline analysis. Series resistance was not compensated; theoretically, this could lead to an underestimation of the extent of desensitization because voltage errors would be larger at the peak current than after receptor desensitization had occurred. However, we previously reported that desensitization rate and extent were not significantly affected by current size for a broad range of amplitudes, including very large current peaks (5–15 nA) that desensitized ~90% over a 28-s application (Bianchi and Mac-

donald, 2002), suggesting that series resistance errors did not significantly affect our interpretations.

Solutions, Drugs, and Drug Application. All the chemicals were purchased from Sigma-Aldrich (St. Louis, MO). External bath solution was composed of 142 mM NaCl, 1 mM CaCl₂, 6 mM MgCl₂, 8 mM KCl, 10 mM glucose, and 10 mM HEPES that was standardized to pH 7.4 with NaOH and osmolality to 323 to 329 mOsm. Recording electrodes were filled with an internal solution consisting of 153 mM KCl, 1 mM MgCl₂, 10 mM HEPES, and 5 mM EGTA at pH 7.3 and osmolality between 301 and 309 mOsm. MgATP (2 mM) was added to the internal solution on recording days. These solutions produced an E_{Cl} near 0 mV and an E_K at -75 mV.

GABA and pentobarbital sodium salt were prepared as stock solutions and were diluted to desired concentrations with external solution on the day of the experiment. Applications of drugs were performed using an ultrafast delivery device consisting of multibarrel tubes (two three-barrel square glass tubing glued together) connected to a perfusion fast-step system, a mechanical translation device (Warner Instrument, Hamden, CT). Each of the three-barrel square glasses was heated and manually pulled to the final barrel size (around 200 μ m). The external bath solution and drug solutions were driven by gravity. This drug delivery device allowed rapid solution exchanges with 10 to 90% rise times consistently less than 2 ms (typically 0.4–1.0 ms) determined by switches between normal and dilute external solution at an open electrode. However, solution exchanges, even when cells were lifted from the recording dish, were likely to occur with a slower rate. Applications of drugs were separated by an interval of at least 45 s to minimize accumulation of desensitization. GABA-evoked single channel activity was recorded with and without pentobarbital application from excised outside-out patches during steady-state conditions (minutes of exposure to GABA). Voltage was clamped at -75 mV during single channel recordings. All the experiments were performed at room temperature.

Data Analysis and Simulations. Whole cell currents were analyzed offline using Clampfit 8.1 (Axon Instruments) and GraphPad Prism 2.01 (GraphPad Software Inc., San Diego, CA). Peak currents were measured directly (manually) relative to the baseline, and residual currents at "steady state" were measured from the end of 28-s application to baseline after recovery. The extent of potentiation of GABA current by pentobarbital was measured by dividing the peak current of coapplication of a given concentration of GABA and pentobarbital by the peak current evoked by GABA alone. The resulting ratio was multiplied by 100 and expressed as percentage of GABA control. The concentration-response data were normalized and fitted using a four-parameter logistic equation with a variable slope: $I = I_{\max}/(1 + 10^{(\text{LogEC}_{50} - \text{Logdrug}) \cdot \text{Hill slope}})$. I represented the current evoked by a given concentration of GABA with or without pentobarbital coapplication. I_{\max} denoted the maximal GABA peak current. The extent of current desensitization was measured as a percentage of current reduction, calculated by dividing the amount of desensitized current (amplitude of peak current - amplitude of current at the end of the 4- or 28-s GABA application) by peak current and multiplying by 100. The rate of deactivation was analyzed using standard exponential Levenberg-Marquardt methods. Deactivation currents were fitted with one or two exponential components in the form of $a_1\tau_1 + a_2\tau_2$, where a_1 and a_2 represented the relative amplitudes of the exponential components, and τ_1 and τ_2 denoted the time constant. A weighted τ was calculated to compare the rates of deactivation using the formula $a_1 \cdot \tau_1/(a_1 + a_2) + a_2 \cdot \tau_2/(a_1 + a_2)$. Single channel data were acquired at 50- μ s intervals, filtered at 2 kHz, and analyzed offline with Fetchan 6.0 (Axon Instruments) using 50% threshold detection. Although most patches contained multiple channels based on overlapped openings, only single amplitude openings were included in the analysis. Kinetic analysis was performed using Interval 5 (Dr. Barry S. Pallotta, University of North Carolina, Chapel Hill, NC). Open duration histograms were generated and fitted by the maximum likelihood method. The number of exponential components was increased until

an additional exponential component did not significantly improve the fit as determined by a log-likelihood ratio test automatically performed by the software. Events with intervals less than 1.5 times of the estimated system dead time (100 μ s) were plotted but not included in the fitting.

Simulations were carried out with the Berkeley Madonna 8.0 software package (www.berkeleymadonna.com), using the fourth order Runge-Kutta algorithm to solve model differential equations with a 100- μ s step size. Simulated currents were imported into GraphPad Prism 2.01 (GraphPad Software Inc.) where noise was added before display.

Data were reported as mean \pm S.E.M. Paired Student's *t* test was used to compare current features before and after pentobarbital treatment. Unpaired Student's *t* test was used to analyze the alterations between different treatment groups. The difference was considered to be statistically significant for *p* < 0.05.

Results

Differential Sensitivity of γ 2L and δ Subunit-Containing GABA_A Receptors to GABA. Whole cell currents were recorded by rapid application of different concentrations of GABA to HEK cells transfected with cDNAs encoding rat α 1, β 3, and γ 2L or α 1, β 3, and δ GABA_A receptor subunits (Fig. 1A). Cells were voltage clamped at -20 mV for cells transfected with α 1, β 3, and γ 2L subunits and at -50 mV for

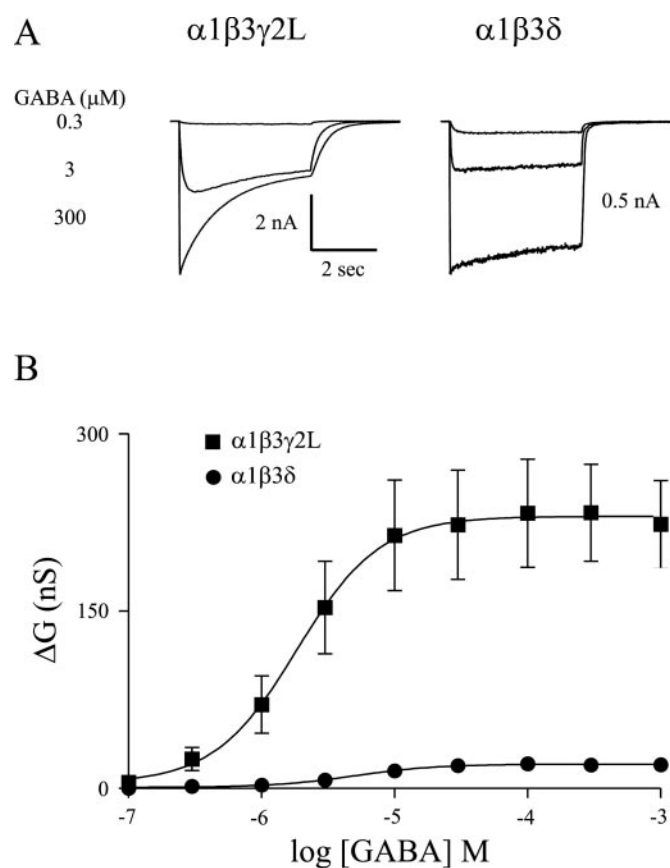


Fig. 1. Differential GABA sensitivity of α 1 β 3 γ 2L and α 1 β 3 δ receptors. A, representative whole cell current traces evoked by different concentrations of GABA from α 1 β 3 γ 2L and α 1 β 3 δ receptors are presented. B, mean peak conductance changes (ΔG) with different GABA concentrations are plotted for α 1 β 3 γ 2L and α 1 β 3 δ receptors. The squares denote the mean peak ΔG for α 1 β 3 γ 2L receptors (*n* = 7), and the circles denote ΔG for α 1 β 3 δ receptors (*n* = 6). The error bars represent S.E.M. (the error bars are too small to be seen for α 1 β 3 δ receptors). The holding potential was -20 mV for α 1 β 3 γ 2L receptors and -50 mV for α 1 β 3 δ receptors.

those transfected with α 1, β 3, and δ subunits due to the smaller amplitude of currents recorded in these receptors (Wohlfarth et al., 2002). No voltage-dependent effects were observed between -20 and -50 mV in the present study (not shown) and a previous report (Wohlfarth et al., 2002). For each GABA concentration, mean peak changes in conductance (ΔG) were greater for α 1 β 3 γ 2L receptors than for α 1 β 3 δ receptors (Fig. 1B). Mean maximal peak ΔG for α 1 β 3 γ 2L receptors (233.4 ± 41.1 nS; *n* = 7) was significantly higher than that for α 1 β 3 δ receptors (21.0 ± 4.0 nS; *n* = 6) (*p* < 0.001). The mean EC₅₀ values for α 1 β 3 γ 2L receptors (8.5 ± 6.4 μ M) and α 1 β 3 δ receptors (5.8 ± 0.7 μ M) were not significantly different. The Hill slope for both α 1 β 3 γ 2L and α 1 β 3 δ receptors was 1.4.

Differences in Direct Activation and Open-Channel Block of γ 2L or δ Subunit-Containing GABA_A Receptors by Pentobarbital. As reported previously (Schulz and Macdonald, 1981; Rho et al., 1996; Thompson et al., 1996; Krampfl et al., 2002), pentobarbital directly activated GABA_A receptors at high concentrations. In the present study, pentobarbital-evoked whole cell currents were recorded from α 1 β 3 γ 2L and α 1 β 3 δ receptors, followed by application of saturating GABA (0.3 mM) for each cell (Fig. 2, A and C). Similar to GABA, pentobarbital evoked smaller mean peak ΔG for α 1 β 3 δ receptors than for α 1 β 3 γ 2L receptors (Fig. 2, B and D, squares). At 1000 μ M pentobarbital, α 1 β 3 δ receptor mean peak ΔG (7.0 ± 2.4 nS; *n* = 7) was significantly smaller than α 1 β 3 γ 2L receptor ΔG (109.4 ± 19.0 nS; *n* = 8) (*p* < 0.001). However, at higher pentobarbital concentrations, the mean peak ΔG for α 1 β 3 γ 2L receptors declined. This effect of high pentobarbital concentration was not observed for α 1 β 3 δ receptors up to 3000 μ M pentobarbital (Fig. 2, B and D, squares). At 3000 μ M pentobarbital, the mean peak ΔG was still significantly smaller for α 1 β 3 δ receptors than for α 1 β 3 γ 2L receptors (*p* < 0.05).

With higher pentobarbital concentrations, a "rebound" current occurred upon washout of pentobarbital (Fig. 2, A and C). This is consistent with rapid unbinding of pentobarbital from a low-affinity, open channel block site as suggested previously (Rho et al., 1996; Thompson et al., 1996; Woollorton et al., 1997; Dalziel et al., 1999; Akk and Steinbach, 2000; Krampfl et al., 2002). For both α 1 β 3 γ 2L and α 1 β 3 δ receptors, the mean peak ΔG of rebound current (measured from the current amplitude at the onset of the rebound current) increased as the pentobarbital concentrations increased from 200 to 3000 μ M (Fig. 2, B and D, circles). The mean peak ΔG of rebound current was significantly less for α 1 β 3 δ receptors than for α 1 β 3 γ 2L receptors at both 1 and 3 mM pentobarbital (*p* < 0.05).

For α 1 β 3 γ 2L receptors, maximal mean peak ΔG evoked by pentobarbital was significantly smaller than mean peak ΔG evoked by a saturating GABA concentration. Maximal mean peak ΔG evoked by pentobarbital averaged $58.5 \pm 8.0\%$ (*p* < 0.01) of GABA-evoked mean peak ΔG . For α 1 β 3 δ receptors, maximal mean peak ΔG evoked by pentobarbital was $127.1 \pm 18.6\%$ of that evoked by a saturating GABA concentration, but this difference did not reach statistical significance. For α 1 β 3 γ 2L receptors, maximal mean rebound ΔG evoked by pentobarbital was significantly smaller than that evoked by a saturating GABA concentration ($80.2 \pm 9.1\%$; *p* < 0.05). However, for α 1 β 3 δ receptors, maximal mean rebound ΔG

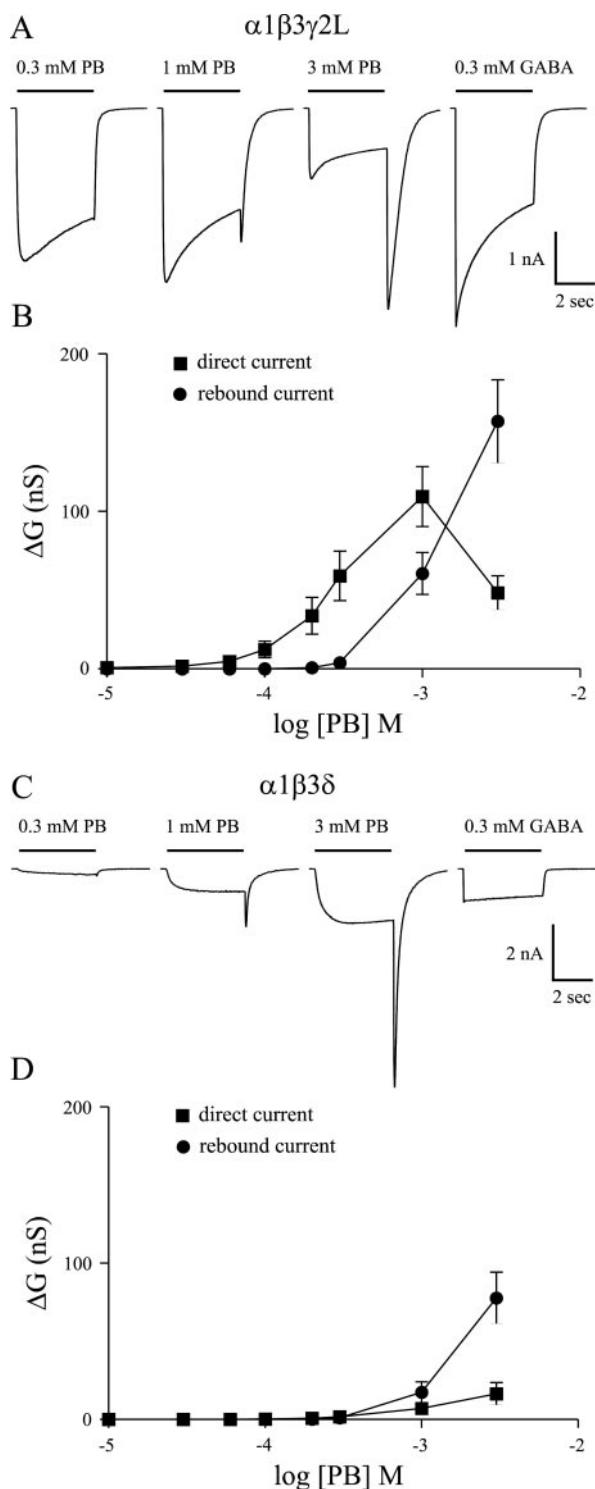


Fig. 2. Characterization of pentobarbital direct activation and open channel block for $\alpha 1\beta 3\gamma 2L$ and $\alpha 1\beta 3\delta$ receptors. **A**, representative currents evoked from the same cell by different concentrations of pentobarbital and 0.3 mM GABA from $\alpha 1\beta 3\gamma 2L$ receptors are presented. **B**, mean peak conductance changes (ΔG) with different pentobarbital concentrations are plotted for direct and rebound currents from $\alpha 1\beta 3\gamma 2L$ receptors ($n = 8$). **C**, representative currents evoked from the same cell by different concentrations of pentobarbital and 0.3 mM GABA from $\alpha 1\beta 3\delta$ receptors are presented. **D**, mean peak ΔG for direct and rebound currents are plotted for $\alpha 1\beta 3\delta$ receptors ($n = 7$). The solid line above each current trace denotes the duration of pentobarbital or GABA application. The squares represent the mean peak ΔG of the direct currents, and the circles represent those of the rebound currents. The error bars denote S.E.M. The holding potential was -20 mV for $\alpha 1\beta 3\gamma 2L$ receptors and -50 mV for $\alpha 1\beta 3\delta$ receptors.

evoked by pentobarbital was $1479.0 \pm 590.4\%$ ($p < 0.01$) of that evoked by a saturating GABA concentration.

For $\alpha 1\beta 3\gamma 2L$ receptors, the pentobarbital-evoked direct current declined during the pentobarbital application (Fig. 2A). This decline likely represented receptor desensitization, although a contribution from open channel block could not be ruled out. This apparent current desensitization was concentration-dependent (300 – 3000 μ M pentobarbital) and was manifested differently in $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ receptors (Fig. 3A). Whereas only minimal desensitization was observed for $\alpha 1\beta 3\delta$ receptor currents up to 3000 μ M pentobarbital (Fig. 3A), more extensive desensitization was observed for $\alpha 1\beta 3\gamma 2L$ receptors at pentobarbital concentrations greater than 300 μ M (Fig. 3A). It is possible, however, that a rapidly equilibrating open channel block mechanism was “masking” macroscopic manifestations of entry into desensitized states, and thus the measurements of apparent desensitization may be underestimated for both isoforms. Furthermore, the activation time with pentobarbital tended to be slower than that observed with GABA, and slow macroscopic activation would preclude observation of fast desensitization (Bianchi and Macdonald, 2002).

For $\alpha 1\beta 3\delta$ receptors, the deactivation rates of GABA-evoked currents were not concentration-dependent for concentrations up to 1 mM (data not shown), but significant slowing of deactivation was observed at 3000 μ M pentobarbital (Figs. 2C and 3B). For $\alpha 1\beta 3\gamma 2L$ receptors, the deactivation rates of GABA-evoked current were not concentration-dependent at concentrations greater than 10 μ M (data not shown). However, the deactivation rates of pentobarbital-evoked current were concentration-dependent at concentrations greater than 300 μ M (Figs. 2A and 3B).

Pentobarbital Enhanced Currents Evoked by a High Concentration of GABA from δ More than $\gamma 2L$ Subunit-Containing GABA_A Receptors. Because low concentrations of pentobarbital (30 – 50 μ M) caused little or no direct activation of current, they were considered modulatory concentrations. Occasionally, pentobarbital at 50 μ M alone produced small direct currents for $\alpha 1\beta 3\gamma 2L$ receptors, but the direct currents were minimal ($<2\%$) compared with maximal GABA-evoked currents. Pentobarbital concentrations in this range potentiated GABA-evoked currents for both $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ receptors. Coapplication of a range of GABA concentrations with 50 μ M pentobarbital slightly potentiated $\alpha 1\beta 3\gamma 2L$ receptor currents (Fig. 4B). The currents evoked by coapplication of GABA and pentobarbital as well as GABA alone were normalized to 300 μ M GABA. The normalized GABA concentration-response curve was shifted upward (Fig. 4B), with a maximal extent of enhancement of $133.9 \pm 19.9\%$ ($n = 8$). The mean EC_{50} for GABA + 50 μ M pentobarbital (3.8 ± 1.9 μ M) was not significantly different from that of GABA alone (8.5 ± 6.4 μ M). Pentobarbital at 30 μ M also potentiated $\alpha 1\beta 3\delta$ receptor currents (Fig. 4C). The concentration-response curve was shifted upward (Fig. 4D), and the amplitude of this shift ($225.9 \pm 15.1\%$; $n = 7$) was significantly greater than that observed with $\alpha 1\beta 3\gamma 2L$ receptors ($p < 0.001$). The mean EC_{50} for GABA + 30 μ M pentobarbital (5.3 ± 1.0 μ M) was not significantly different from that of GABA alone (5.8 ± 0.7 μ M).

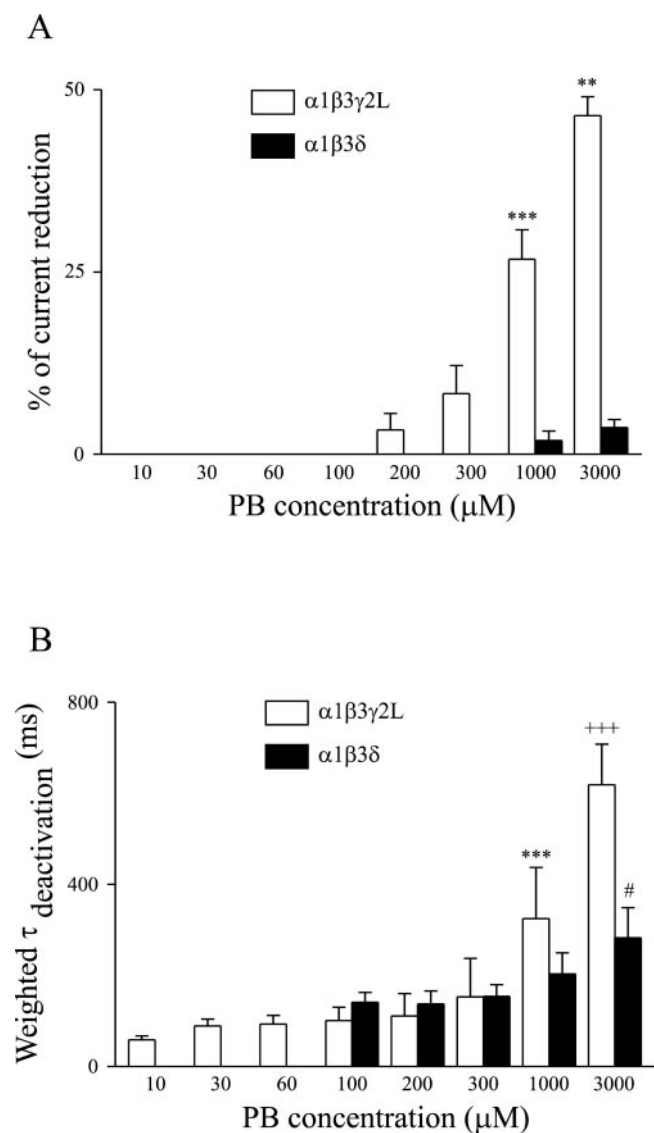


Fig. 3. Characterization of the apparent desensitization and deactivation of $\alpha 1\beta 3\gamma 2L$ and $\alpha 1\beta 3\delta$ receptors currents evoked by pentobarbital. **A**, mean amounts of desensitization evoked by pentobarbital for $\alpha 1\beta 3\gamma 2L$ and $\alpha 1\beta 3\delta$ receptors were determined. The percentage of current reductions (desensitization) was increased in a concentration-dependent manner from 300 to 3000 μM pentobarbital for $\alpha 1\beta 3\gamma 2L$ receptors. For the $\alpha 1\beta 3\delta$ receptors, only minimal desensitization (2–3% current reduction) was observed at 1000 and 3000 μM pentobarbital. **B**, mean rates of deactivation evoked by pentobarbital for $\alpha 1\beta 3\gamma 2L$ and $\alpha 1\beta 3\delta$ receptors were determined. The rate of deactivation was increased in a concentration dependent manner from 300 to 3000 μM pentobarbital for $\alpha 1\beta 3\gamma 2L$ receptors. For $\alpha 1\beta 3\delta$ receptors, the mean weighted deactivation time constant was significantly greater at 3000 μM than at 1000 μM pentobarbital. The blank columns represent the mean apparent desensitization or deactivation of $\alpha 1\beta 3\gamma 2L$ receptors ($n = 8$), and the filled columns represent those of $\alpha 1\beta 3\delta$ receptors ($n = 7$). Absence of columns indicates that the measurements could not be made due to either small amplitude currents or lack of measurable desensitization. The error bars denote the S.E.M. Significantly different from 1000 μM pentobarbital at **, $p < 0.01$; #, $p < 0.05$; +++, $p < 0.001$. Significantly different from 300 μM pentobarbital at ***, $p < 0.001$.

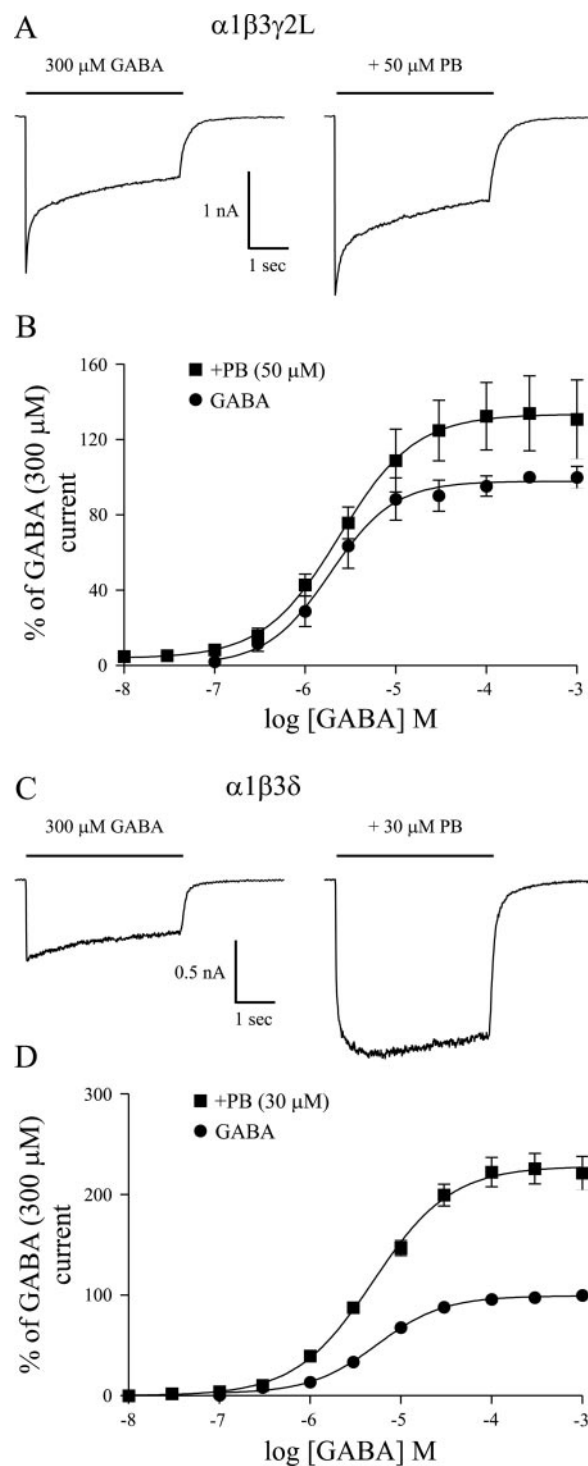


Fig. 4. Pentobarbital at modulatory concentrations produced greater enhancement of $\alpha 1\beta 3\delta$ receptor than $\alpha 1\beta 3\gamma 2L$ receptor currents. **A**, representative current traces evoked by 300 μM GABA and coapplication of 300 μM GABA and 50 μM pentobarbital from $\alpha 1\beta 3\gamma 2L$ receptors are presented. **B**, concentration-response curves for GABA alone ($n = 7$) and coapplication of GABA with 50 μM pentobarbital ($n = 8$) are plotted for $\alpha 1\beta 3\gamma 2L$ receptors. **C**, representative current traces evoked by 300 μM GABA and coapplication of 300 μM GABA and 30 μM pentobarbital from $\alpha 1\beta 3\delta$ receptors are presented. **D**, concentration-response curves for GABA alone ($n = 6$) and coapplication of GABA with 30 μM pentobarbital ($n = 7$) are plotted for $\alpha 1\beta 3\delta$ receptors. The solid line above each representative current trace denotes the duration of drug application. The squares represent the mean normalized response of coapplication of GABA and pentobarbital, and the circles represent that of GABA alone. The error bars denote the S.E.M. (the error bars in **D** are too small to be seen).

Pentobarbital Produced Similar Alterations in Peak Current, Desensitization, and Deactivation of Currents Evoked by a Submaximal Concentration of GABA for δ and γ 2L Subunit-Containing GABA_A Receptors. To demonstrate better the fast component of desensitization and to determine the effect of pentobarbital on GABA_A receptor currents evoked by low (1 μ M) GABA concentrations during coapplication, cells were lifted from the recording dishes, and pentobarbital was preapplied for 1.5 s before a 4-s coapplication of GABA and pentobarbital. Pentobarbital (100 μ M, a concentration that evoked very small currents from both $\alpha\beta\gamma$ 2L and $\alpha\beta\delta$ receptors) substantially enhanced both $\alpha\beta\gamma$ 2L ($660.5 \pm 111.9\%$; $n = 6$) and $\alpha\beta\delta$ ($872.0 \pm 105.9\%$; $n = 8$) receptor currents, but no significant difference in enhancement was observed between these two isoforms (Fig. 5, A–C). When activated by 1 μ M GABA, $\alpha\beta\gamma$ 2L and $\alpha\beta\delta$ receptor currents showed minimal apparent desensitization ($<3\%$; Fig. 5, A, B, and D). Coapplication of 1 μ M GABA with 100 μ M pentobarbital significantly increased the extent of desensitization similarly for both $\alpha\beta\gamma$ 2L and $\alpha\beta\delta$ receptors ($\sim 10\%$; Fig. 5, A, B, and D) ($p < 0.01$). For these experiments, the extent of current loss during the 4-s applications was used to describe desensitization, rather than fitted desensitization time constants, because the rate of decay was slow relative to the application length, precluding accurate fitting of the time constants.

The currents evoked by 1 μ M GABA deactivated significantly faster for $\alpha\beta\delta$ receptors than for $\alpha\beta\gamma$ 2L receptors

(Fig. 5, A, B, and E) ($p < 0.001$). For $\alpha\beta\delta$ receptors, the mean current deactivation time constants were significantly increased by pentobarbital from 86.8 ± 12.4 to 271.8 ± 45.9 ms ($p < 0.01$). In the presence of pentobarbital, the mean current deactivation time constants were significantly increased from 321.2 ± 29.4 to 1257.4 ± 237.9 ms for $\alpha\beta\gamma$ 2L receptors ($p < 0.05$). The mean current deactivation time constants in the presence of pentobarbital were significantly smaller for $\alpha\beta\delta$ receptors than for $\alpha\beta\gamma$ 2L receptors ($p < 0.001$) (Fig. 5E).

Pentobarbital Evoked a Greater Enhancement of Peak Amplitude and Desensitization with a Saturating Concentration of GABA for δ than for γ 2L Subunit-Containing GABA_A Receptors. Although pentobarbital (100 μ M) modulation of currents evoked by a 4-s application of low concentration of GABA (1 μ M) was not significantly different between $\alpha\beta\delta$ and $\alpha\beta\gamma$ 2L receptors, modulation of currents evoked by a 4-s application of a saturating concentration of GABA (1 mM) by pentobarbital (100 μ M) produced a much larger effect on $\alpha\beta\delta$ than $\alpha\beta\gamma$ 2L currents (we used the same preapplication protocol as that for application of 1 μ M GABA). Pentobarbital did not enhance the peak $\alpha\beta\gamma$ 2L receptor current evoked by 1 mM GABA ($99.4 \pm 5.8\%$; $n = 7$) (Fig. 6, A and C). However, pentobarbital evoked a substantial enhancement in peak $\alpha\beta\delta$ receptor current ($526.4 \pm 98.3\%$; Fig. 6, B and C). Note that in the coapplication condition under which $\alpha\beta\gamma$ 2L receptor

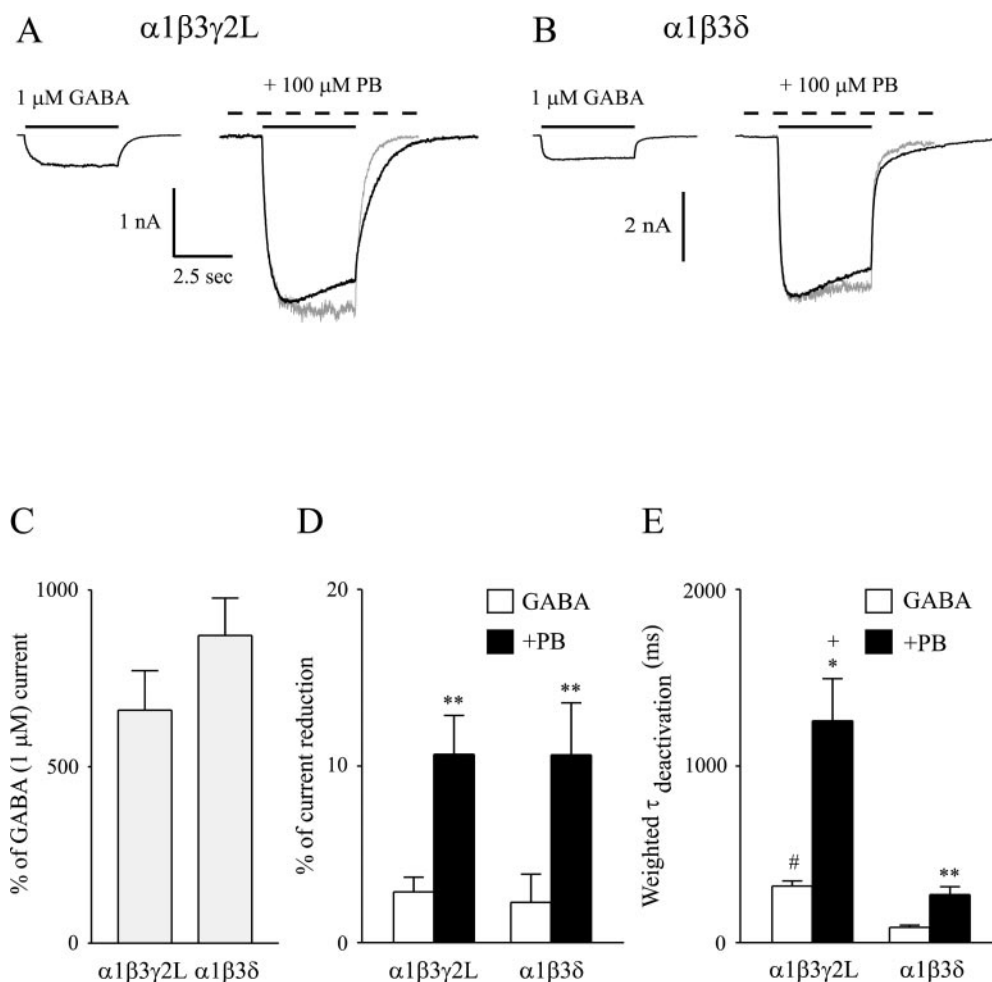


Fig. 5. Coapplication (4 s) of 1 μ M GABA with 100 μ M pentobarbital produced similar alterations in enhancement, desensitization, and deactivation for $\alpha\beta\gamma$ 2L and $\alpha\beta\delta$ receptors. A, representative current traces evoked by 1 μ M GABA and coapplication of 1 μ M GABA with 100 μ M pentobarbital from $\alpha\beta\gamma$ 2L receptors are presented. The GABA control trace (gray trace) was normalized to the pentobarbital enhanced trace to show the changes in desensitization and deactivation evoked by coapplication of GABA and pentobarbital. B, representative current traces evoked by 1 μ M GABA and coapplication of 1 μ M GABA with 100 μ M pentobarbital from $\alpha\beta\delta$ receptors are presented. C, pentobarbital potentiation of GABA currents are plotted for both $\alpha\beta\gamma$ 2L ($n = 6$) and $\alpha\beta\delta$ receptors ($n = 8$). D, mean apparent desensitization evoked by 1 μ M GABA and coapplication of 1 μ M GABA with 100 μ M pentobarbital is plotted. E, mean rate of current deactivation evoked by 1 μ M GABA and coapplication of 1 μ M GABA with 100 μ M pentobarbital is plotted. The solid line above each current trace denotes the duration of GABA application, and the dashed line denotes that of pentobarbital application. The blank columns represent the mean desensitization or deactivation of GABA alone treatment, and the filled columns represent that of coapplication of GABA and pentobarbital. The error bars denote the S.E.M. Significantly different from corresponding GABA control at *, $p < 0.05$, **, $p < 0.01$. Significantly different from GABA control in δ isoform at #, $p < 0.001$. Significantly different from coapplication of GABA and pentobarbital in δ isoform at +, $p < 0.001$.

GABA concentration-response curves were generated, 50 μ M pentobarbital potentiated currents evoked by 300 μ M GABA. The basis for the difference between this enhancement compared with results with 100 μ M pentobarbital preapplied for 1.5 s before a jump into 1 mM GABA is unclear but may be related to increased direct gating of the receptors (visible during the preapplication period) that may have resulted in a small amount of "predesensitization", similar to what has been described for preincubation in low concentrations of GABA (Overstreet et al., 2000).

Currents evoked from $\alpha 1\beta 3\gamma 2L$ receptors by 1 mM GABA exhibited substantial desensitization ($78.5 \pm 3.5\%$; Fig. 6, A and D), consistent with previous studies on recombinant GABA_A receptors containing a γ subunit (Haas and Macdonald, 1999; Burkat et al., 2001; Bianchi and Macdonald, 2002). However, only minimal desensitization was observed for $\alpha 1\beta 3\delta$ receptors with this concentration of GABA ($14.1 \pm$

3.9%; Fig. 6, B and D), similar to our previous reports (Haas and Macdonald, 1999). Pentobarbital differentially altered desensitization for $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ receptor currents evoked by 1 mM GABA. The mean percentage of current reduction was significantly increased to $39.1 \pm 6.3\%$ ($p < 0.01$) for $\alpha 1\beta 3\delta$ receptors. In contrast, the mean percentage of current reduction was significantly decreased by pentobarbital by $\sim 10\%$ to $69.5 \pm 5.5\%$ for $\alpha 1\beta 3\gamma 2L$ receptors ($p < 0.05$) (Fig. 6D).

To evaluate more accurately the effects of pentobarbital on the extent of desensitization, longer duration GABA applications were required for the residual currents to approach a quasi steady state. Thus, both $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ currents were evoked by long-duration (28-s) pulses of GABA (1 mM). The enhancement of peak currents for long-duration GABA application was within the range of that for 4-s applications for both isoforms. However, the extent of desensitization,

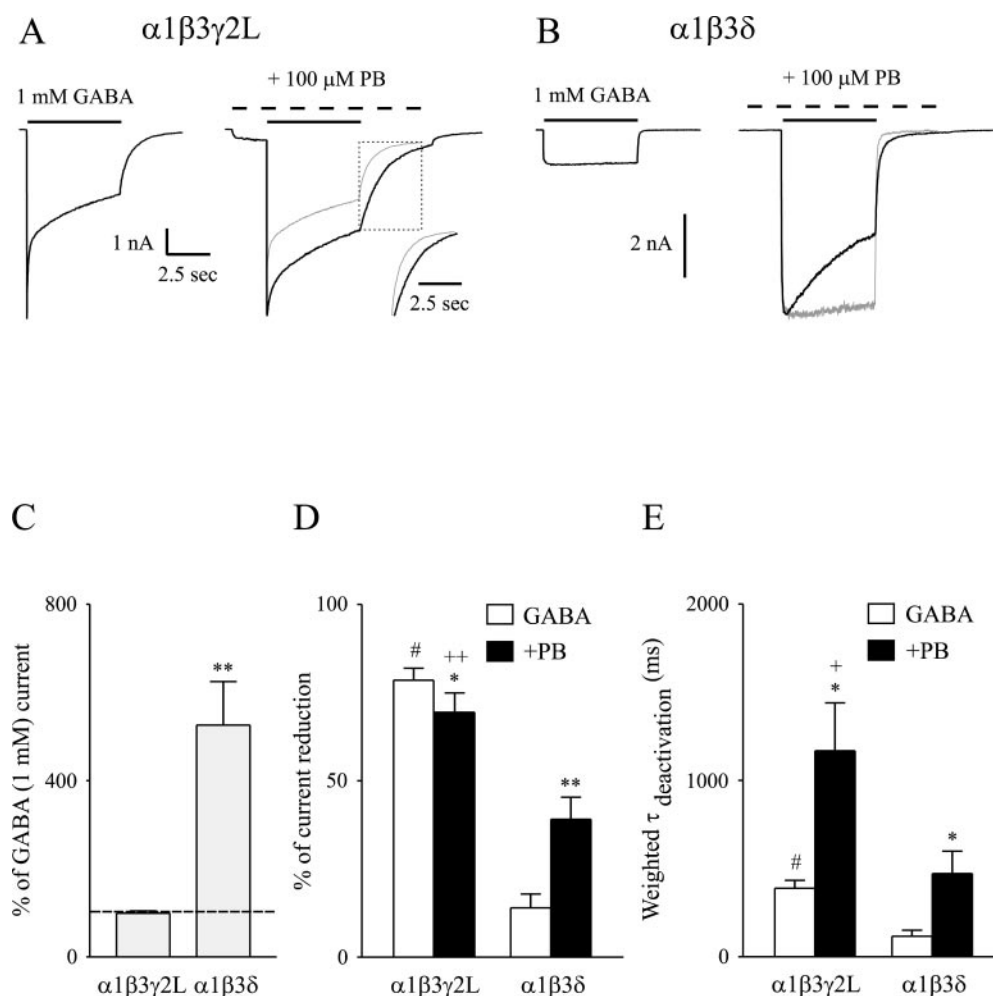


Fig. 6. Coapplication (4 s) of 1 mM GABA with 100 μ M pentobarbital produced differential alterations in enhancement and desensitization for $\alpha 1\beta 3\gamma 2L$ and $\alpha 1\beta 3\delta$ receptors. A, representative current traces evoked by 1 mM GABA and coapplication of 1 mM GABA with 100 μ M pentobarbital from $\alpha 1\beta 3\gamma 2L$ receptors. The GABA control trace (gray trace) was normalized to the trace evoked by coapplication of GABA and pentobarbital to show the changes in desensitization and deactivation. B, representative current traces evoked by 1 mM GABA and coapplication of 1 mM GABA with 100 μ M pentobarbital from $\alpha 1\beta 3\delta$ receptors. C, pentobarbital differentially affected the mean GABA peak currents for $\alpha 1\beta 3\gamma 2L$ ($n = 7$) and $\alpha 1\beta 3\delta$ ($n = 8$) receptors. The dashed line indicates 100%. D, comparison of the mean apparent desensitization evoked by 1 mM GABA and coapplication of 1 mM GABA with 100 μ M pentobarbital. E, comparison of the mean rate of current deactivation evoked by 1 mM GABA and coapplication of 1 mM GABA with 100 μ M pentobarbital. The solid line above each representative current trace denotes the duration of GABA application, and the dashed line denotes that of pentobarbital application. The blank columns represent the mean apparent desensitization or deactivation of GABA alone treatment. The filled columns represent that of coapplication of GABA and pentobarbital. The error bars denote the S.E.M. *, significantly different from corresponding GABA control at $p < 0.05$; **, significantly different from $\gamma 2L$ isoform or GABA control at $p < 0.01$; #, significantly different from GABA control in δ isoform at $p < 0.001$. Significantly different from coapplication of GABA and pentobarbital in δ isoform at +, $p < 0.05$; ++, $p < 0.01$.

compared with 4-s applications, was increased for both isoforms. Specifically, pentobarbital significantly increased the mean residual currents from 868.0 ± 338.1 to 1196.0 ± 392.0 pA for $\alpha 1\beta 3\gamma 2L$ receptors ($n = 5$) ($p < 0.05$) as a consequence of a significant reduction in the extent of desensitization from 83.8 ± 2.9 to $78.1 \pm 2.2\%$ ($p < 0.05$) after 28-s GABA application (Fig. 7, A–C). For $\alpha 1\beta 3\delta$ receptors ($n = 4$), pentobarbital induced a significant increase in apparent desensitization from 30.0 ± 9.6 to $59.6 \pm 10.6\%$ ($p < 0.05$) after 28-s GABA application, but the mean residual current amplitudes were significantly increased after pentobarbital treatment from 252.5 ± 60.1 to 512.5 ± 121.5 pA ($p < 0.05$) (Fig. 7, D–F).

Although pentobarbital produced differential changes in enhancement of peak current and desensitization for $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ receptor currents evoked by a saturating concentration of GABA, the rates of deactivation were prolonged in the presence of pentobarbital in both of these receptors after 4-s GABA application (Fig. 6, A and B). The mean current deactivation time constants after activation with 1 mM GABA alone were significantly smaller for $\alpha 1\beta 3\delta$ receptors than for $\alpha 1\beta 3\gamma 2L$ receptors ($p < 0.001$) (Fig. 6E). Pentobarbital significantly increased the mean current deactivation time constants from 118.2 ± 32.4 to 471.9 ± 127.8 ms ($p < 0.05$) for $\alpha 1\beta 3\delta$ receptors and also significantly increased the mean current deactivation time constants from 388.8 ± 44.6 to 1168.9 ± 272.1 ms for $\alpha 1\beta 3\gamma 2L$ receptors ($p < 0.05$) (Fig. 6E).

Pentobarbital Introduced a Long-Duration Open State for δ Subunit-Containing GABA_A Receptor Single Channel Currents. To explore possible bases for the different effects of pentobarbital in modulating macroscopic GABA-evoked currents from δ and $\gamma 2L$ subunit-containing GABA_A receptors, single channel currents were recorded without and with pentobarbital during steady-state application of GABA to outside-out membrane patches containing $\alpha 1\beta 3\delta$ or $\alpha 1\beta 3\gamma 2L$ receptors. Data were analyzed from 40 to 480 s after the patch was excised. $\alpha 1\beta 3\gamma 2L$ receptor single channel currents exhibited bursting openings in the presence of 1 mM GABA (Fig. 8A1–3). The distribution of open states was fitted best with three exponential functions (Fig. 8A4), similar to our previous reports (Fisher and Macdonald, 1997b; Haas and Macdonald, 1999). Coapplication of 1 mM GABA with 100 μ M pentobarbital increased the mean duration of channel openings (Fig. 8B1–3), although the distribution of open states was still best described by three exponential functions (Fig. 8B4). Compared with GABA alone, pentobarbital significantly increased the mean channel open duration from 1.45 ± 0.26 ms ($n = 5$) to 4.86 ± 1.06 ms ($n = 5$) for $\alpha 1\beta 3\gamma 2L$ receptors ($p < 0.05$) (Table 1). The time constant of the shortest exponential function (τ_1) was not significantly altered by pentobarbital. However, pentobarbital significantly decreased the relative area of the shortest exponential function (A_1) ($p < 0.05$) (Table 1). Neither the time constant (τ_2) nor the relative area (A_2) of the second exponential function was significantly altered for $\alpha 1\beta 3\gamma 2L$ receptors (Table 1). Interestingly, the third exponential function time constant (τ_3) was significantly increased from 4.63 ± 0.81 to 9.37 ± 1.11 ms ($p < 0.01$), and the relative area (A_3) was significantly increased from 18.2 ± 3.04 to $41.4 \pm 7.21\%$ ($p < 0.05$) (Table 1). Pentobarbital at 100 μ M alone directly activated single channel currents (Fig. 8C1–3). The open-duration histogram of channel activity evoked by 100

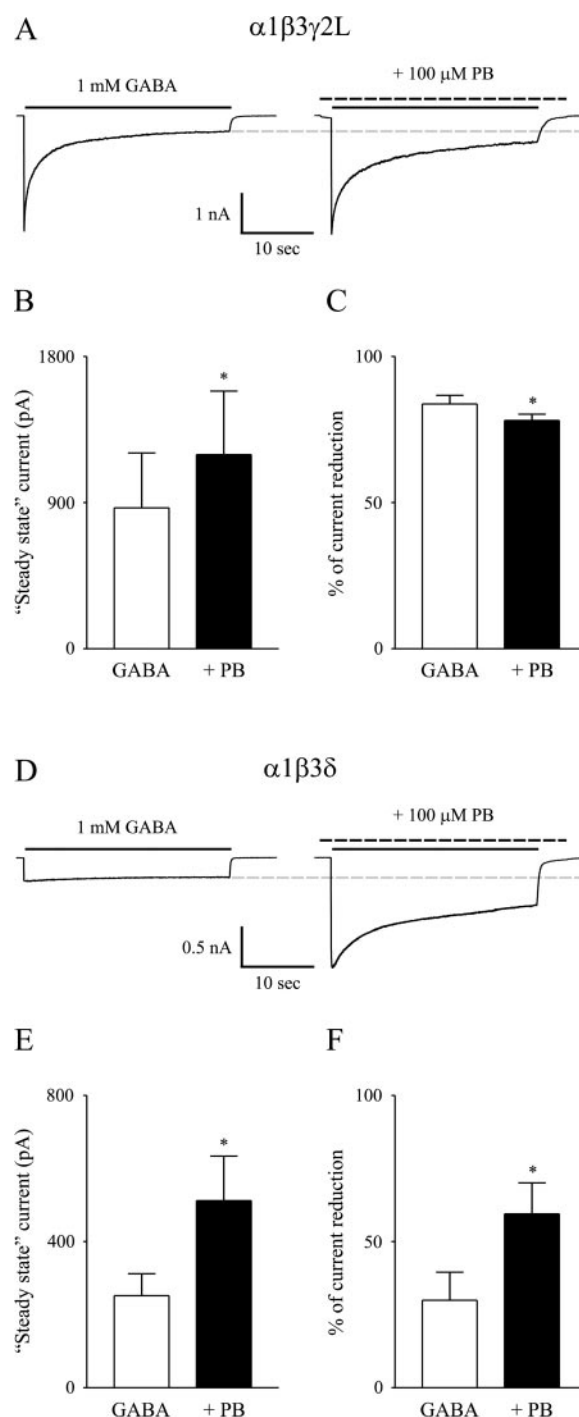


Fig. 7. Pentobarbital significantly enhanced the residual currents for both $\alpha 1\beta 3\gamma 2L$ and $\alpha 1\beta 3\delta$ receptors after long-duration (28 sec) application of GABA. A, representative current traces evoked by 1 mM GABA (28 s) and coapplication of 1 mM GABA with 100 μ M pentobarbital from $\alpha 1\beta 3\gamma 2L$ receptors. B, pentobarbital significantly enhanced the mean residual currents at steady state for $\alpha 1\beta 3\gamma 2L$ receptors ($n = 5$). C, pentobarbital significantly decreased the apparent desensitization for $\alpha 1\beta 3\gamma 2L$ receptors ($n = 5$). D, representative current traces evoked by 1 mM GABA (28 s) and coapplication of 1 mM GABA with 100 μ M pentobarbital from $\alpha 1\beta 3\delta$ receptors. E, pentobarbital significantly enhanced the mean residual currents at steady state for $\alpha 1\beta 3\delta$ receptors ($n = 4$). F, pentobarbital significantly increased the apparent desensitization for $\alpha 1\beta 3\delta$ receptors ($n = 4$). The solid line above each representative current trace denotes the duration of GABA application, and the dashed line denotes that of pentobarbital application. The gray dashed line indicates the level of residual current for GABA controls. The error bars denote the S.E.M. *, significantly different from GABA control at $p < 0.05$.

μ M pentobarbital ($n = 4$) was similar to that evoked by 1 mM GABA (Fig. 8A1 and C1), except that τ_1 was significantly smaller with pentobarbital alone treatment ($p < 0.05$). Com-

pared with pentobarbital alone, the mean open duration and τ_3 were significantly increased with coapplication of GABA and pentobarbital ($p < 0.05$) (Table 1).

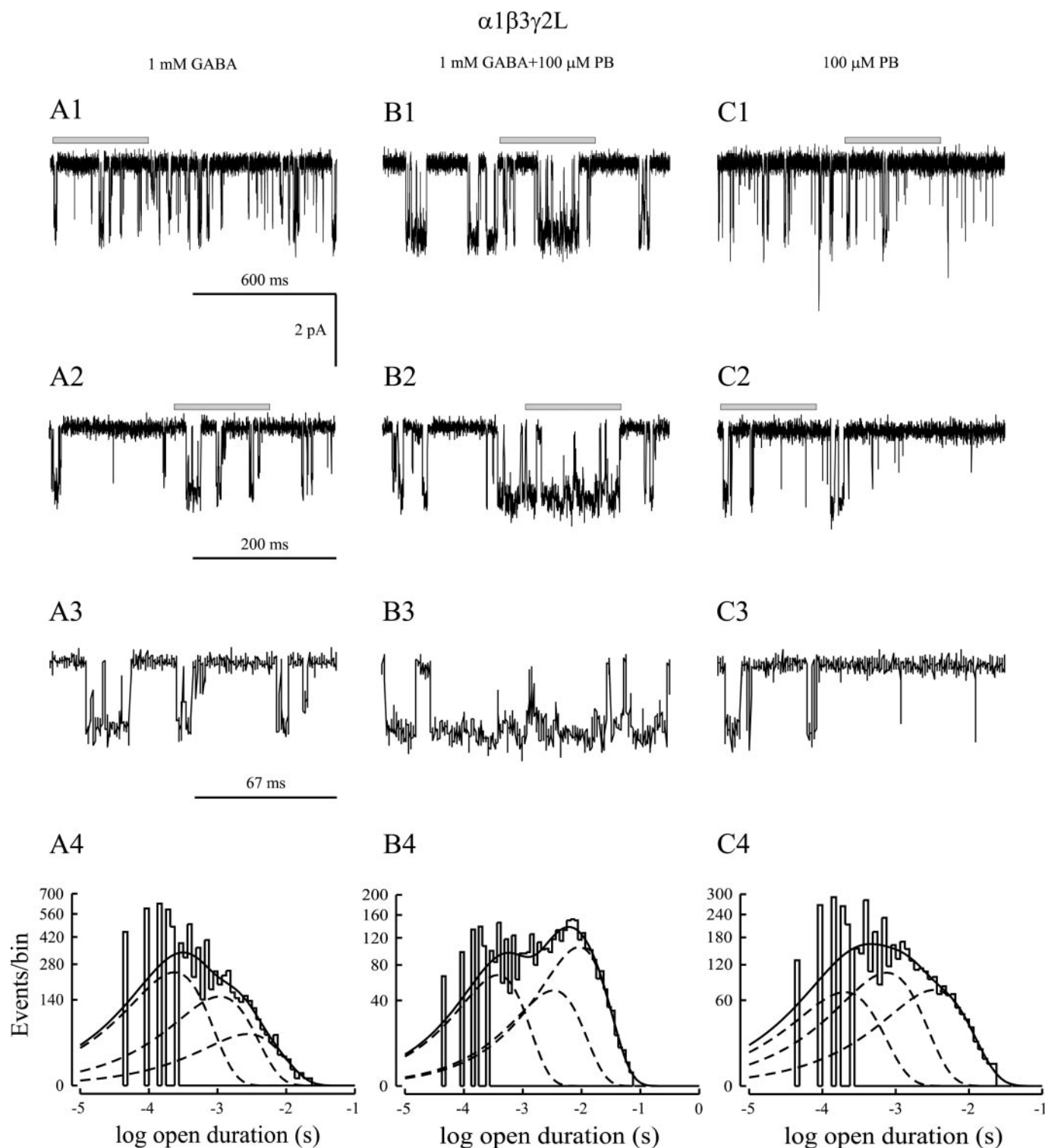


Fig. 8. Single channel $\alpha 1\beta 3\gamma 2L$ receptor currents evoked by 1 mM GABA, coapplication of 1 mM GABA and 100 μ M pentobarbital, or 100 μ M pentobarbital alone. The portion of each single channel current trace (A1, B1, and C1) below the hatched column was expanded and shown in A2, B2, and C2, and a portion of each trace (A2, B2, and C2) was shown in A3, B3, and C3. Compared with the single channel current evoked by 1 mM GABA or 100 μ M pentobarbital, the open duration of single current was prolonged with coapplication of GABA and pentobarbital. The distributions of open states for each treatment are plotted in A4, B4, and C4. The open events for A4, B4, and C4 were 7351, 3976, and 4229, respectively. Each histogram contained the data from a single patch. Note that the time constants and relative areas of the third open states were increased by coapplication of GABA and pentobarbital (the x-axis values for B4 are different than those of A4 and C4).

In contrast to the “high-efficacy” bursting behavior of $\alpha 1\beta 3\gamma 2L$ receptor single channel currents, $\alpha 1\beta 3\delta$ receptor single channel currents displayed only brief openings (Fig. 9A1–3). The distribution of open states was fitted best with two exponential functions (Fig. 9A4), similar to our previous reports (Fisher and Macdonald, 1997b; Haas and Macdonald, 1999). Coapplication of 1 mM GABA with 100 μ M pentobarbital resulted in an increased mean open duration (Fig. 9B1–3). The distribution of open states in the presence of pentobarbital, however, required three exponential functions (Fig. 9B4). Compared with GABA alone, coapplication of GABA and pentobarbital significantly increased the mean open duration from 0.53 ± 0.04 ms ($n = 6$) to 1.08 ± 0.17 ms ($n = 7$) for $\alpha 1\beta 3\delta$ receptors ($p < 0.05$) (Table 1). A_1 was significantly decreased by pentobarbital ($p < 0.05$), although τ_1 was not significantly altered. τ_2 was significantly increased from 0.90 ± 0.10 to 1.27 ± 0.10 ms in the presence of pentobarbital ($p < 0.05$). Coapplication of GABA and pentobarbital introduced a third longer duration open state for $\alpha 1\beta 3\delta$ receptors with a time constant of 4.03 ± 0.59 ms and relative area of $10.3 \pm 2.15\%$ (Table 1). The single channel activity evoked by 100 μ M pentobarbital alone ($n = 5$) was different from that evoked by 1 mM GABA alone because open-state distributions required a third longer-duration open state ($\tau_3 = 2.95 \pm 0.62$ ms, $A_3 = 3.50 \pm 0.57\%$) (Fig. 9C1–4). τ_1 was significantly smaller for pentobarbital alone treatment than for GABA alone treatment ($p < 0.001$) (Table 1). Compared with pentobarbital alone, the mean open duration ($p < 0.05$), τ_1 ($p < 0.001$), τ_2 ($p < 0.01$), and A_3 ($p < 0.05$) were significantly greater with coapplication of GABA and pentobarbital (Table 1).

Although it was possible that pentobarbital altered closed times or opening frequency in these experiments, we could not accurately analyze these properties because most patches in the current study exhibited overlapping openings, which indicated the presence of multiple active channels. The presence of more than one channel will result in spuriously high measures of open probability and open frequency, as well as low apparent closed duration measurements. Analysis was performed only on individual open durations; burst analysis was not performed due to the presence of multichannel patches that precluded accurate closed state analysis (required to define intraburst closed durations).

Simulation of $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ Receptor Currents. Although a detailed mechanism of action for pentobarbital could not be proposed based on the current results, we felt that simulations may shed light on two interesting features of the macroscopic data. First, pentobarbital potentiated the peak amplitude of $\alpha 1\beta 3\delta$ currents but did not potentiate that of $\alpha 1\beta 3\gamma 2L$ currents evoked by a saturating GABA concentration, despite the clear increase in efficacy by prolonging steady-state mean open time. Although this might have been related to limitations of resolving the “true” peak of a rapidly activating and desensitizing current using whole cell methods, could this observation be related to underlying receptor kinetics? Second, pentobarbital exhibited opposite effects on the macroscopic desensitization of $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ currents. Although this could be related to isoform-specific pentobarbital modulation of rate constants of desensitized states, was it possible that an increase in single channel open time could partly contribute to both of these apparently opposite effects? To explore these issues, we generated simulated currents using our previously established models for $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ receptors (Haas and Macdonald, 1999) (Fig. 10, A and B). For the purposes of this analysis, we were limited to qualitative comparisons, particularly because the models were generated using data obtained with excised patches, a condition of substantially higher temporal resolution than the whole cell configuration (Bianchi and Macdonald, 2002).

In the first set of simulations, the currents evoked by 6-square pulses of 1 mM agonist were modeled for the $\alpha 1\beta 3\gamma 2L$ receptor (Fig. 10, A and C). Compared with the “wild-type” current (left trace), increasing the duration of O_2 by 3-fold (second trace) caused a small increase in peak current ($\sim 10\%$), whereas the residual current increased by $\sim 100\%$ (dotted lines). Combining this with a 3-fold increase in O_3 duration (third trace), no further change in peak was observed, whereas the residual current amplitude was increased by an additional $\sim 100\%$. Finally, β_3 and α_3 were altered to reflect the observed changes in single channel open distribution (right trace). In this case, peak amplitude changed by $\sim 5\%$, whereas the residual current was 3-fold larger. This limited change in peak amplitude was attributed in part to rapid entry into the fast desensitized state, effec-

TABLE 1

Pentobarbital (100 μ M) modulated the open states of GABA_A receptors

For $\alpha 1\beta 3\gamma 2L$ receptors, the average number of openings were 3758 (GABA), 3899 (GABA + pentobarbital), and 3645 (pentobarbital); and for $\alpha 1\beta 3\delta$ receptors, 5309 (GABA), 4320 (GABA + pentobarbital), and 3499 (pentobarbital).

	$\alpha 1\beta 3\gamma 2L$			$\alpha 1\beta 3\delta$		
	GABA (1 mM)	+ PB (100 μ M)	PB (100 μ M)	GABA (1 mM)	+ PB (100 μ M)	PB (100 μ M)
<i>n</i>	5	5	4	6	7	5
Mean	1.45 ± 0.26	$4.86 \pm 1.06^{a,c}$	1.41 ± 0.19	0.53 ± 0.04	$1.08 \pm 0.17^{a,c}$	0.48 ± 0.07
τ_1 (ms)	0.31 ± 0.02	0.32 ± 0.07	0.24 ± 0.01^f	0.33 ± 0.02	0.35 ± 0.03^e	0.18 ± 0.02^g
A_1 (%)	49.2 ± 3.33	33.2 ± 5.34^a	46.0 ± 6.39	65.0 ± 2.87	54.4 ± 2.81^a	61.1 ± 3.26
τ_2 (ms)	1.55 ± 0.39	2.28 ± 0.58	1.11 ± 0.13	0.90 ± 0.10	$1.27 \pm 0.10^{a,d}$	0.75 ± 0.10
A_2 (%)	32.7 ± 3.01	25.4 ± 3.33	32.9 ± 2.92	35.1 ± 2.88	35.3 ± 1.97	35.4 ± 2.87
τ_3 (ms)	4.63 ± 0.81	$9.37 \pm 1.11^{b,c}$	4.66 ± 0.67		4.03 ± 0.59	2.95 ± 0.62
A_3 (%)	18.2 ± 3.04	41.4 ± 7.21^a	21.2 ± 4.33		10.3 ± 2.15^c	3.50 ± 0.57

PB, pentobarbital.

^a Significantly different from corresponding GABA control at $p < 0.05$.

^b Significantly different from corresponding GABA control at $p < 0.01$.

^c Significantly different from corresponding PB at $p < 0.05$.

^d Significantly different from corresponding PB at $p < 0.01$.

^e Significantly different from corresponding PB at $p < 0.001$.

^f Significantly different from corresponding GABA at $p < 0.05$.

^g Significantly different from corresponding GABA at $p < 0.001$.

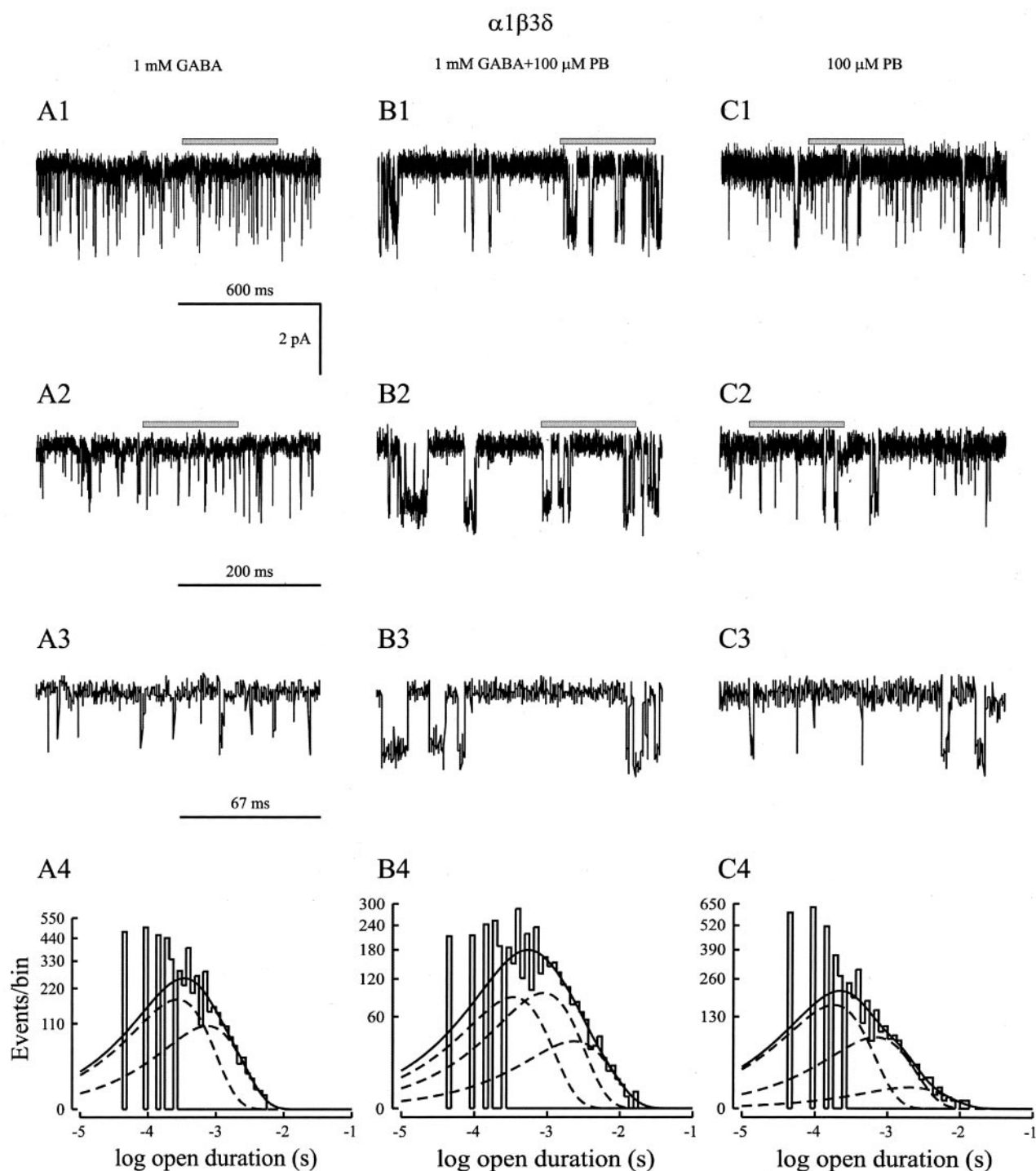


Fig. 9. Single channel $\alpha 1\beta 3\delta$ receptor currents evoked by 1 mM GABA, coapplication of 1 mM GABA and 100 μ M pentobarbital, or 100 μ M pentobarbital alone. The portion of each single current trace (A1, B1, and C1) below the hatched column was expanded proportionally and shown in A2, B2, and C2, and a portion of each trace (A2, B2, and C2) was shown in A3, B3, and C3. Compared with the single channel current evoked by 1 mM GABA or 100 μ M pentobarbital, the open duration of single current was prolonged with coapplication of GABA and pentobarbital. The distributions of open states for each treatment are plotted in A4, B4, and C4. The open events for A4, B4, and C4 were 4890, 3767, and 4257, respectively. Each histogram contained the data from a single patch. Note that coapplication of GABA and pentobarbital introduced an additional open state, which was not seen with GABA alone. Three open states were observed with pentobarbital treatment alone.

tively truncating the current by preventing some channels from opening upon agonist binding. Also, the model predicts that >90% of the peak amplitude is due to openings into the second open state (whereas residual current is dominated by O_3). Although we have not evaluated this experimentally

(but see Burkat et al., 2001), this kinetic arrangement predicted that increasing the duration and/or proportion of O_3 would preferentially increase residual currents. Apparent desensitization was reduced for each condition, consistent with our previous experimental and simulation results re-

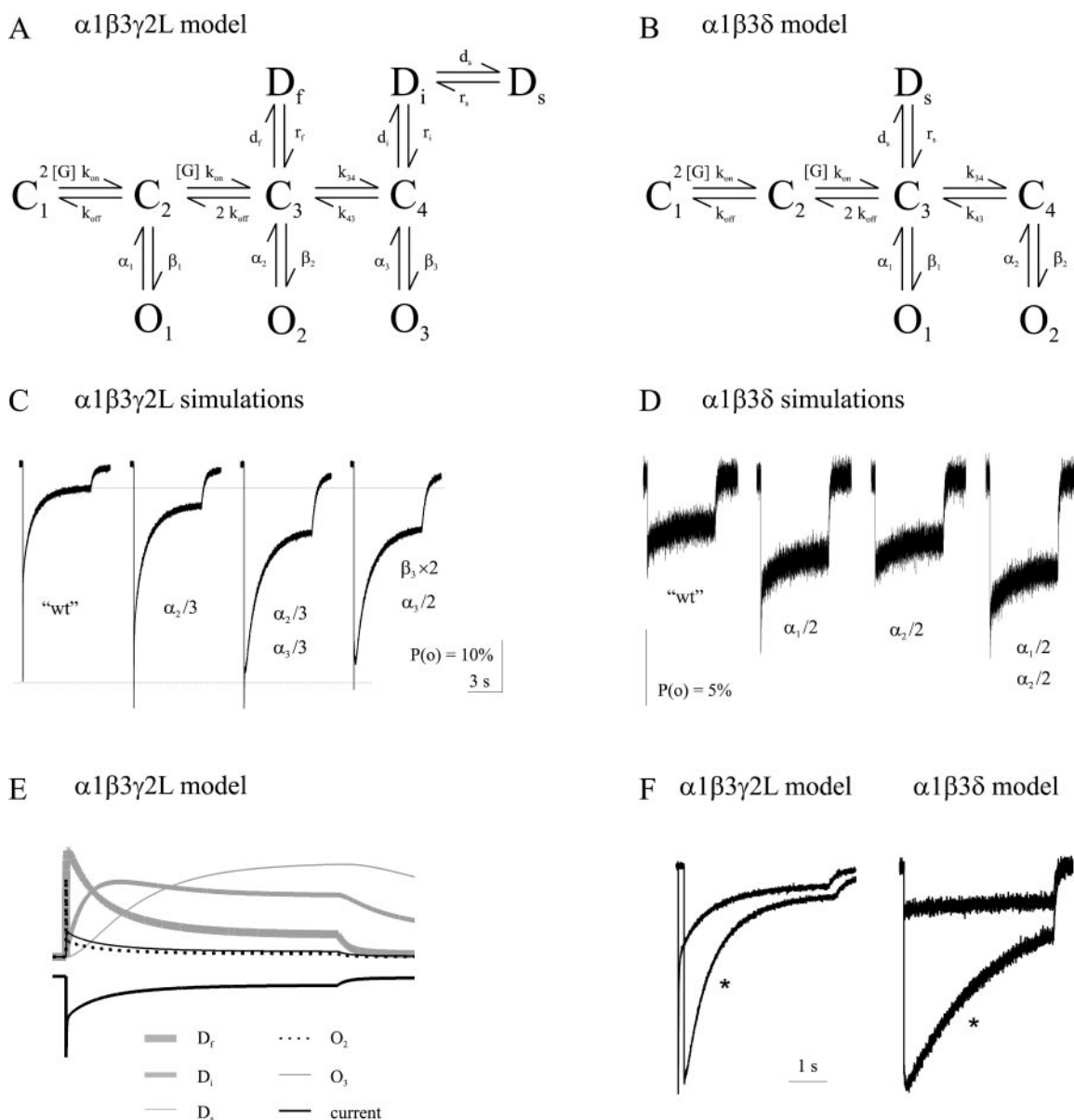


Fig. 10. Simulations of $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ receptor currents. A, kinetic model of $\alpha 1\beta 3\gamma 2L$ receptor behavior (from Haas and Macdonald, 1999). Rate constants were $k_{on} = 7.0e + 6 \text{ s} \cdot \text{M}^{-1}$, $k_{off} = 170 \text{ s}^{-1}$, $C_{34} = 710 \text{ s}^{-1}$, $C_{43} = 58 \text{ s}^{-1}$, $\beta_1 = 50 \text{ s}^{-1}$, $\beta_2 = 1800 \text{ s}^{-1}$, $\beta_3 = 76 \text{ s}^{-1}$, $\alpha_1 = 3100 \text{ s}^{-1}$, $\alpha_2 = 280 \text{ s}^{-1}$, $\alpha_3 = 150 \text{ s}^{-1}$, $D_f = 960 \text{ s}^{-1}$, $R_f = 22 \text{ s}^{-1}$, $D_i = 8 \text{ s}^{-1}$, $R_i = 0.81 \text{ s}^{-1}$, $D_s = 0.75 \text{ s}^{-1}$, $R_s = 0.49 \text{ s}^{-1}$; for clarity, intraburst closed states proceeding from each open state were omitted from the figure (see Haas and Macdonald, 1999). B, kinetic model of $\alpha 1\beta 3\delta$ receptor current response to 1 mM GABA. Rate constants were $k_{on} = 6.5e + 6 \text{ s} \cdot \text{M}^{-1}$, $k_{off} = 18 \text{ s}^{-1}$, $C_{34} = 12 \text{ s}^{-1}$, $C_{43} = 11 \text{ s}^{-1}$, $\beta_1 = 80 \text{ s}^{-1}$, $\beta_2 = 9 \text{ s}^{-1}$, $\alpha_1 = 2400 \text{ s}^{-1}$, $\alpha_2 = 600 \text{ s}^{-1}$, $D_s = 0.35 \text{ s}^{-1}$, $R_s = 0.35 \text{ s}^{-1}$; for clarity, intraburst closed states proceeding from each open state were omitted from the figure (see Haas and Macdonald, 1999). C, simulations of $\alpha 1\beta 3\gamma 2L$ receptor-current response to 1 mM GABA under control condition (left trace), as well as decreasing α_2 by 3 (second trace), decreasing both α_2 and α_3 by a factor of 3 (third trace), and decreasing α_3 by a factor of 2 and increasing β_3 by a factor of 2 to reflect the observed changes in O_3 time constant and relative proportion (right trace). For each trace, the current was generated using a 6 s square pulse of 1 mM GABA. Gaussian noise was added to each current with a standard deviation of 0.5 (on a scale of 0–100 open probability percentage). Dotted lines show the level of the peak and residual current for the control (left) trace for comparison with other conditions. D, simulations of $\alpha 1\beta 3\delta$ receptors under control conditions (left trace), with α_1 decreased by a factor of 2 (second trace), with α_2 decreased by a factor of 2 (third trace), or both (right trace). For each trace, the current was generated using a 6-s square pulse of 1 mM GABA. Gaussian noise was added to the currents with a standard deviation of 0.5 (on a scale of 0–100 open probability percentage). The apparent increase in noise reflects the decreased open probability of this model relative to the $\alpha 1\beta 3\gamma 2L$ model. The horizontal time scale is the same as that in C. E, simulation showing the occupancy of various states of the $\alpha 1\beta 3\gamma 2L$ kinetic model during a simulated 6-s application of 1 mM GABA. The total open probability (i.e., the sum of states O_1 , O_2 , and O_3) were shown as downward going and represented the shape of the predicted current. Overlaid upward going lines were the probability density functions of the three desensitized states, O_2 and O_3 (O_1 and other closed states were not shown). F, Simulations of $\alpha 1\beta 3\gamma 2L$ (left) and $\alpha 1\beta 3\delta$ receptors (right) generated to reflect observed macroscopic currents in the presence of pentobarbital. For the $\alpha 1\beta 3\gamma 2L$ model, the following rate constants were changed: $\beta_2 = 1450$, $\beta_3 = 150$, $\alpha_2 = 200$, $\alpha_3 = 75$, and $R_i = 0.4$. The resulting trace was overlaid and shifted to the right for comparison (but was not normalized). For the $\alpha 1\beta 3\delta$ model, the “control” rate constants were altered in the following way to more closely represent our whole cell observations: $C_{43} = 22$ and $\beta_2 = 18$. The following additional changes were made to reflect the presence of pentobarbital: $\beta_1 = 400$, $\beta_3 = 90$, $\beta_2 = 10$, $\alpha_3 = 250$, $\alpha_2 = 450$, $D_s = 0.17$, and $R_s = 0.07$. No intraburst closed states were added to state O_3 . *, simulations that reflect the presence of pentobarbital.

garding increased efficacy (Bianchi and Macdonald, 2001). This general pattern of macroscopic manifestations of increasing open duration (i.e., preferential increases in residual current) was observed for less complex models as well, as long as desensitized states did not proceed directly from the open state (not shown). These simulations illustrate the principle that increasing open duration can produce selective increases in residual, as opposed to peak, current amplitudes for $\alpha 1\beta 3\gamma 2L$ receptors, in part because of the rapid entry into a fast desensitized state.

Similar simulations were also carried out with a model generated for $\alpha 1\beta 3\delta$ receptors (Fig. 10, B and D). Note that these receptors are characterized by substantially smaller open probabilities relative to $\alpha 1\beta 3\gamma 2L$ receptors, even under conditions of saturating GABA. This was apparent in the relative increase in "noise" that was added as Gaussian noise with a constant standard deviation for both sets of simulations. Increasing the open duration via decreasing α_1 by a factor of 2 resulted in an approximate doubling of both the peak and the steady-state current amplitude (Fig. 10D, left trace, second trace). This can be explained by the relative contribution of O_1 to the current time course. Similar to $\alpha 1\beta 3\gamma 2L$ receptor model, the first accessible open state (in this case O_1) contributes >90% of the peak current amplitude. However, in contrast to the $\alpha 1\beta 3\gamma 2L$ model, initial access to this state is not significantly compromised by rapid entry into a desensitized state (allowing peak current enhancement), and this open state continues to pass a considerable portion of the total current throughout the pulse, accounting for ~60% of the residual amplitude (not shown). Thus, all parts of the current are sensitive to changes in this open state. Consistent with this idea, when the duration of O_2 was increased by a factor of 2 (Fig. 10D, third trace), the macroscopic residual current was preferentially increased, with only minor changes in peak amplitude. Interestingly, in contrast to the clear decrease in apparent desensitization observed with increased open duration for $\alpha 1\beta 3\gamma 2L$ currents, apparent desensitization was slightly increased for $\alpha 1\beta 3\delta$ currents (from ~40 to ~50%). This difference is attributable to isoform differences in baseline gating efficacy and desensitization, which will limit changes in peak amplitude for $\alpha 1\beta 3\gamma 2L$ but not $\alpha 1\beta 3\delta$ receptor currents. When an additional open state was included (arbitrarily made to proceed from the closed state C_4), to reflect our single channel observations, no alteration of peak current amplitudes was observed (data not shown). This is consistent with "proximal" open states (with relatively high entry rate constants) selectively contributing to the initial development of current. Again, although the exact mechanism of pentobarbital modulation remains unclear, the simulations suggested that longer duration openings could manifest differently for receptors with different baseline kinetic properties.

The simulated currents from both $\alpha 1\beta 3\gamma 2L$ and $\alpha 1\beta 3\delta$ receptor models were qualitatively in agreement with our experimental observations, regarding the differential sensitivities of peak and residual current amplitude to pentobarbital modulation. However, the quantitative differences in these amplitude measurements suggested that additional kinetic parameters, in addition to mean open duration, contributed to the alterations induced by pentobarbital. For example, the residual current amplitude was overestimated in the case of $\alpha 1\beta 3\gamma 2L$ receptor simulations (Fig. 10C),

whereas the peak current amplitude changes for $\alpha 1\beta 3\delta$ receptors were underestimated (Fig. 10D). Clearly, quantitative correlations of steady state mean open time changes evoked by pentobarbital with peak or residual macroscopic currents are not straightforward because occupancy of open states is only a small fraction of all bound states. This is illustrated in Fig. 10E, in which a simulated $\alpha 1\beta 3\gamma 2L$ receptor current (downward trace) is shown with the corresponding probability density functions of the two open and three desensitized states available to the fully bound receptor. For clarity, occupancy of C_3 , C_4 , and the intraburst closed states is not shown, which also contributes to the overall occupancy patterns. Thus, further simulations were carried out to explore other possible mechanisms of pentobarbital modulation of macroscopic currents of $\alpha 1\beta 3\gamma 2L$ and $\alpha 1\beta 3\delta$ receptors. Because of the number of unconstrained parameters in these complex models, we did not attempt to uniquely fit all rate constants to our experimental data. Instead, focused changes were made in an attempt to generate hypotheses as to which additional parameters might be involved in pentobarbital modulation. For $\alpha 1\beta 3\gamma 2L$ receptors, reducing the exit rate of D_i by a factor of 2 (in addition to the changes made to reflect the single channel open distribution data) reduced the residual current amplitude (by decreasing open probability) with minimal alteration of the peak amplitude (Fig. 10F, left traces). Similar results were obtained with increasing entry into D_i by a factor of 1.5. For the $\alpha 1\beta 3\delta$ receptor model, we first altered certain parameters to render currents that more closely resembled our whole cell observations (that is, less macroscopic desensitization than observed in outside out patches) (Fig. 10F; see legend for rate constant changes). From this baseline, we altered various parameters, in addition to the changes to reflect the single channel data. Specifically, increasing the opening rate β_1 by a factor of 5 (with or without corresponding 5-fold increases in β_2 and β_3) resulted in an appropriate 5-fold increase in peak current, but also a 5-fold increase in residual current (not shown). To more closely reflect our observations, we also changed desensitization by both increasing entry into and decreasing exit from the single desensitized state to obtain the current shown in Fig. 10F (right traces). Because this entry rate was still slower than β_1 , the peak amplitude was minimally affected, but the steady-state occupancy of the desensitized state was increased, and thus the residual current (as well as the increase in apparent desensitization) was similar to our experimental observations. Further single channel and macroscopic experiments would be required to test the hypothesis that these kinetic parameters were altered in the presence of pentobarbital for each of these isoforms.

Discussion

Direct Effects of Pentobarbital on $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ GABA_A Receptors. Similar to many allosteric modulators, at sufficiently high concentrations pentobarbital can directly activate GABA_A receptor currents. Here, we report notable differences between its activity at $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ receptors. For example, like the isoform-specific GABA-evoked currents, pentobarbital evoked desensitizing currents from $\alpha 1\beta 3\gamma 2L$ receptors, whereas currents from $\alpha 1\beta 3\delta$ receptors were essentially nondesensitizing. Although this is consistent with minimal desensitization being a prop-

erty of δ subunit-containing isoforms, as we have suggested previously, we cannot rule out the possibility that desensitization could be observed upon activation by a "full" agonist. We have inferred that desensitized states are in fact accessible to $\alpha\beta\delta$ isoforms because GABA-evoked currents in the presence of tetrahydrodeoxycorticosterone or pentobarbital show increased desensitization (Wohlfarth et al., 2002; this study).

Direct activation of single channel events showed isoform differences as well. Pentobarbital seemed to be a higher efficacy agonist than GABA for $\alpha1\beta3\delta$ receptors, because a third open state was observed (not seen with GABA), consistent with a recent report for $\alpha4\beta2\delta$ receptors (Akk et al., 2004). At the whole cell level, the amplitude of pentobarbital-evoked currents (measured at the peak of the rebound) was significantly larger than maximal GABA-evoked currents from the same cells. These observations are consistent with the proposed idea that GABA may be a partial agonist at this isoform, which may provide the capacity for substantial modulation (relative to $\alpha\beta\gamma$ isoforms) by a variety of compounds (Lees and Edwards, 1998; Adkins et al., 2001; Thompson et al., 2002; Bianchi and Macdonald, 2003; Wallner et al., 2003; Akk et al., 2004).

Pentobarbital Modulation of $\alpha1\beta3\delta$ and $\alpha1\beta3\gamma2L$ Receptor Single Channel Behavior. Pentobarbital increased mean $\alpha1\beta3\delta$ receptor open duration approximately 2-fold, predominantly due to the introduction of a third, longer duration open state. This fundamental change in gating was reminiscent of that observed with neurosteroid modulation (Wohlfarth et al., 2002). Pentobarbital also increased $\alpha1\beta3\gamma2L$ receptor mean single channel open duration (by ~ 3 -fold), but did so by a different mechanism than that observed for $\alpha1\beta3\delta$ receptors, increasing the relative proportion and duration of the third open state. This finding is similar to reports on pentobarbital modulation of native and recombinant ($\alpha1\beta2\gamma2L$) receptor currents (Macdonald et al., 1989; Steinbach and Akk, 2001), but in the spinal neuron preparations, the duration of the third open state was unaltered. Although this modulation was significant, pentobarbital did not introduce an additional open state because three open states were available to channels bound by GABA alone; pentobarbital seemed to modulate an already available open state. The differences in gating efficacy between $\alpha1\beta3\delta$ and $\alpha1\beta3\gamma2L$ receptors in response to GABA may underlie some of the macroscopic differences in pentobarbital modulation that we observed (see below).

Pentobarbital Modulation of Macroscopic GABA-Evoked Currents from $\alpha1\beta3\delta$ and $\alpha1\beta3\gamma2L$ Receptors. Pentobarbital potentiated peak currents evoked by both low and high GABA concentration for $\alpha1\beta3\delta$ receptors, but only those evoked by low GABA concentration for $\alpha1\beta3\gamma2L$ receptors. The selective enhancement of peak currents for low but not high GABA concentrations has been observed for many modulators, including benzodiazepines and neurosteroids. Although the precise mechanism for this difference remains unclear, we propose that it depended in part on kinetic differences in response to GABA between these isoforms. For $\alpha1\beta3\delta$ receptors, the peak open probability was low (Fisher and Macdonald, 1997b) and similar (within a factor of 2) throughout 28-s GABA applications (Bianchi and Macdonald, 2002; this study). In contrast, the peak open probability of the high-efficacy $\alpha1\beta3\gamma2L$ receptors was ~ 10 -fold higher

than the steady-state open probability ($\sim 90\%$ desensitization in 28 s). Simulations predicted that peak open probability (40%) was only slightly changed with simulated increases in gating efficacy. This limited change in peak open probability was not exhibited for models of low-efficacy, minimally desensitizing receptors (such as $\alpha1\beta3\delta$ receptors). Pentobarbital potentiation of both $\alpha1\beta3\gamma2L$ and $\alpha1\beta3\delta$ receptor peak currents evoked by low concentration of GABA (a condition in which both isoforms have low efficacy) is consistent with this modeling. The simulations provided a potential explanation for our observation that saturating GABA-evoked peak $\alpha1\beta3\delta$ but not $\alpha1\beta3\gamma2L$ peak currents were potentiated by pentobarbital: low-efficacy channel behavior, particularly in the context of minimal desensitization, is preferentially susceptible to positive allosteric modulation. Similar observations of selective allosteric enhancement of $\alpha\beta\delta$ peak currents (relative to $\alpha\beta\gamma$ isoforms) have been reported for neurosteroids (Wohlfarth et al., 2002), as well as other modulators (Lees and Edwards, 1998; Thompson et al., 2002; Wallner et al., 2003).

Although pentobarbital differentially modulated the peak currents evoked by saturating GABA for $\alpha1\beta3\delta$ and $\alpha1\beta3\gamma2L$ receptors, the residual currents for both of these isoforms were enhanced by pentobarbital. Simulations suggested that changes in opening rate and desensitization, in addition to mean open time, may also be involved in pentobarbital modulation of these isoforms. For example, pentobarbital may result in a decrease in open frequency (due to increased stability of a desensitized state) for $\alpha1\beta3\gamma2L$ receptors (Fig. 10F). Consistent with this, pentobarbital was reported to decrease single channel steady-state opening frequency in spinal neurons (Macdonald et al., 1989).

Pentobarbital Modulation of Desensitization and Deactivation of $\alpha1\beta3\delta$ and $\alpha1\beta3\gamma2L$ Receptors. Interestingly, we found that pentobarbital differentially affected macroscopic desensitization of $\alpha1\beta3\delta$ and $\alpha1\beta3\gamma2L$ receptor currents, resulting in increased desensitization of $\alpha1\beta3\delta$ receptor currents but decreased desensitization of $\alpha1\beta3\gamma2L$ receptor currents. The increased mean open duration of GABA-evoked $\alpha1\beta3\gamma2L$ receptor single channel currents by pentobarbital might account for the apparent slowing of desensitization, as we have argued previously using a mutation that decreased apparent desensitization secondary to increased gating efficacy (Bianchi and Macdonald, 2001). However, pentobarbital might directly alter $\alpha1\beta3\gamma2L$ receptor desensitization. Our simulations suggested the possibility that increased gating efficacy and increased stability of the intermediate desensitized state may together account for the experimental observations. In this setting, the indirect reduction (related to efficacy) was partially balanced by an increase in microscopic desensitization, with the net result being less extensive desensitization.

In contrast, coapplication of pentobarbital with a saturating GABA concentration increased desensitization of $\alpha1\beta3\delta$ receptors. Similar observations of increased gating efficacy together with increased desensitization were reported for neurosteroid modulation of $\alpha1\beta3\delta$ receptors (Wohlfarth et al., 2002). Although it was possible that the new longer open state observed in the presence of pentobarbital was "coupled" somehow to desensitized states, there is experimental evidence of gating and desensitization varying independently (Bianchi and Macdonald, 2001, 2003), and rapid desensitiza-

tion has been reported for $\alpha 1\beta 3$ and $\alpha 1\beta 3\epsilon$ receptors, both of which exhibit only two open states (Fisher and Macdonald, 1997b; Neelands et al., 1999). As suggested by the simulations, the macroscopic manifestation of desensitization depends on the underlying gating efficacy. Interestingly, the effect is opposite for high- and low-efficacy receptors. When efficacy is low at baseline, increasing it may actually enhance macroscopic desensitization; when efficacy is high at baseline, further increases tend to reduce the rate and extent of desensitization. In both settings, macroscopic desensitization is changed without altering desensitized states. In addition, pentobarbital may directly alter the slow desensitized state of $\alpha 1\beta 3\delta$ receptors because, like the $\alpha 1\beta 3\gamma 2L$ receptor model, changes in the stability of the desensitized state (in combination with changes in gating efficacy) of the $\alpha 1\beta 3\delta$ receptor model produced simulated currents that were similar to our experimental observations (Fig. 10F).

We observed that the mean current deactivation time constants were prolonged for both $\alpha 1\beta 3\delta$ and $\alpha 1\beta 3\gamma 2L$ receptors, similar to reports in cultured hippocampal neurons (Rho et al., 1996). Increased desensitization is one mechanism by which deactivation may be prolonged (Jones and Westbrook, 1995; Haas and Macdonald, 1999), but this was not observed for $\alpha 1\beta 3\gamma 2L$ receptor currents. We have shown that deactivation can be prolonged by increased channel open time (Bianchi and Macdonald, 2001), as well as increased agonist affinity (K. F. Haas and R. L. Macdonald, unpublished). The present data are consistent with the conclusion that prolongation of deactivation together with decreased desensitization for $\alpha 1\beta 3\gamma 2L$ receptors was due in part to an increase in channel open time. In principle, it is possible that pentobarbital increased the affinity for GABA, but this (in addition to the increase in efficacy) would predict a reduction of GABA EC_{50} that was not observed here. Our previous simulations showed that, for simple models, deactivation was clearly sensitive to increased opening rate (Bianchi and Macdonald, 2001), consistent with our hypothesis that opening frequency was changed for $\alpha 1\beta 3\delta$ receptors.

Implications of Pentobarbital Enhancement of Tonic, Extra- or Perisynaptic δ Subunit-Containing Receptor Currents. Barbiturates such as pentobarbital are thought to depress neuronal activity by prolongation of inhibitory postsynaptic currents (Poisbeau et al., 1997; Rovira and Ben-Ari, 1999). However, the role of CNS depressants and anesthetics on extra- or perisynaptic inhibition has remained largely unknown. The current study suggested that pentobarbital may selectively modulate δ subunit-containing GABA_A receptors. Although $\alpha\beta\gamma$ isoforms also exist at non-synaptic locations, δ subunit-containing GABA_A receptors are targeted exclusively to extra- or perisynaptic sites. Pentobarbital enhancement of tonic inhibition, and in particular that mediated by $\alpha\beta\delta$ isoforms, may contribute to its anesthetic effect in the CNS.

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