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Blockade of Glutamate Receptors and Barbiturate Anesthesia

Increased Sensitivity to Pentobarbital-induced Anesthesia Despite Reduced Inhibition of AMPA Receptors in GluR2 *Null Mutant Mice*

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Background: **Barbiturates enhance γ-aminobutyric acid type A ($GABA_A$) receptor function and also inhibit the α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) subtype of glutamate receptor. The relative contribution of these actions to the behavioral properties of barbiturates is not certain. Because AMPA receptor complexes that lack the *GluR2* subunit are relatively insensitive to pentobarbital inhibition, *GluR2* null mutant mice provide a novel tool to investigate the importance of AMPA receptor inhibition to the anesthetic effects of barbiturates.**

Methods: ***GluR2*** **null allele (−/−), heterozygous (+/−), and wild-type (+/+) mice were injected with pentobarbital (30 and 35 mg/kg intraperitoneally). Sensitivity to anesthetics was assessed by measuring the latency to loss of righting reflex, sleep time, and the loss of corneal, pineal, and toe-pinch withdrawal reflexes. In addition, patch-clamp recordings of acutely dissociated CA1 hippocampal pyramidal neurons from (−/−) and (+/+) mice were undertaken to investigate the effects of barbiturates on kainate-activated AMPA receptors and GABA-activated $GABA_A$ receptors.**

Results: **Behavioral tests indicate that sensitivity to pentobarbital was increased in (−/−) mice. In contrast, AMPA receptors from (−/−) neurons were less sensitive to inhibition by pentobarbital (concentrations that produced 50% of the maximal inhibition [IC_{50}], 301 *vs.* 51 μM), thiopental (IC_{50}, 153 *vs.* 34 μM), and phenobarbital (IC_{50}, 930 *vs.* 205 μM) compared with wild-type controls, respectively. In addition, the potency of kainate was greater in (−/−) neurons, whereas no differences were observed for the potentiation of $GABA_A$ receptors by pentobarbital.**

Conclusions: **The *GluR2* null mutant mice were more sensitive to pentobarbital anesthesia despite a reduced sensitivity of *GluR2*-deficient AMPA receptors to barbiturate blockade. Our results indicate that the inhibition of AMPA receptors does not correlate with the anesthetic effects of barbiturates in this animal model. We postulate that the increase in the sensitivity to anesthetics results from a global suppression of excitatory neurotransmission in *GluR2*-deficient mice. (Key words: Electrophysiology; knockout; righting reflex; voltage clamp.)**

NORMAL neuronal transmission depends on the delicate balance between excitatory and inhibitory synaptic inputs. General anesthetics, including barbiturates, are thought to depress neuronal function by disrupting this interplay. Barbiturates enhance the activity of γ-aminobu-

tyric acid type A ($GABA_A$) receptors, thereby facilitating inhibitory postsynaptic currents.[1] Barbiturates also inhibit the α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) subtype of glutamate receptors at clinically relevant concentrations. Although the relative importance of glutamate receptors to the anesthetic effects of barbiturates is not certain, the anticonvulsant[2] and neuroprotective[3] effects of barbiturates have been attributed, in part, to the inhibition of AMPA receptors.

Glutamate is the major excitatory neurotransmitter in the central nervous system, and the AMPA subtype of glutamate receptor mediates the fast component of excitatory postsynaptic currents.[4,5] AMPA receptors consist of protein subunits that assemble into pentameric[6] or tetrameric[7,8] structures that contain an intrinsic channel pore. Based on sequence homology, four subunit genes have been identified and are referred to as *GluR1* to *GluR4*.[9] The expression of these genes and the splicing and editing of their pre-mRNA products[10,11] vary in different populations of neurons, resulting in a diversity of AMPA receptors.[12]

The physiologic and pharmacologic properties of native and recombinant AMPA receptors critically depend on the subunit composition. For example, the presence of the *GluR2* subunit confers a ninefold to 30-fold[13,14] decrease in calcium (Ca^{2+}) permeability to AMPA receptors.[15] This reduced Ca^{2+} permeability is attributed to a positively charged arginine (R) residue in the membrane reentrant pore loop (M2) of the *GluR2* subunit. The gene for the *GluR2* subunit codes for an uncharged glutamine (Q); however, the codon is "edited" at the pre-mRNA stage to one encoding arginine at the "Q/R edited site" in the 586 position of M2.[11,16] The other AMPA receptor subunits (*GluR1*, *GluR3*, and *GluR4*) are unedited and contain a neutral glutamine residue at this site.

AMPA receptors that contain the *GluR2* subunit are further characterized by a reduced sensitivity to endogenous and exogenous polyamines[17,18] and an increased sensitivity to barbiturates.[19,20] The resistance of *GluR2*-containing receptors to polyamines is attributed to the charged arginine residue at the Q/R edited site that repels the positive charge of polyamines. The mechanism underlying the altered sensitivity of *GluR2*-containing receptors to barbiturates is less certain because barbiturates are relatively uncharged at physiologic *p*H. Nevertheless, recombinant receptors that lack the *GluR2* subunit[19] or its Q/R edited site[20] demonstrate a fivefold to 10-fold reduced sensitivity to pentobarbital, respectively. These results predict that neurons deficient of the *GluR2* subunit would be less sensitive to barbiturate inhibition.

Null mutant mice, deficient of the *GluR2* subunit, were recently developed by Jia *et al.*[13] Gene targeting in embryonic stem cells allowed the disruption of the M1 and pore loop regions of the *GluR2* gene, preventing the expression of the entire *GluR2* subunit. *GluR2* null allele mutants are fertile but show poor parenting ability, are smaller during early development, and have a higher postnatal mortality. However, their weight and size are similar to normal littermates by 5 to 7 weeks, and, subsequently, they have a normal life expectancy.[13] Adult *GluR2* null mutant mice demonstrate decreased exploratory behaviors and impaired motor coordination.[13] Nevertheless, they demonstrate a brisk righting reflex and no differences in corneal, pineal, or toe-pinch withdrawal reflexes under control conditions.

GluR2 null allele mutant mice provide an experimental model to study the correlation between the *in vivo* sensitivity to barbiturates and blockade of AMPA receptors *in vitro*. We tested the hypothesis that *GluR2*-deficient mice demonstrate a decreased sensitivity to the anesthetic effects of barbiturates compared with wild-type littermates because of the reduced blockade of AMPA receptors.

Materials and Methods

Behavioral Study of Anesthetic Sensitivity

The sensitivity to pentobarbital was investigated in 28 *GluR2* null mutant (−/−), 45 wild-type (+/+), and 26 heterozygous (+/−) littermate mice older than 6 weeks of age. Pentobarbital 30 mg/kg (Somnotol, MTC Pharmaceuticals, Cambridge, Ontario, Canada; 65 mg/ml diluted to 1 mg/ml in 0.9% normal saline) was injected intraperitoneally after an aspiration test. The mice were then placed in a plastic container that was warmed by a heat lamp. An investigator who was blinded to the genotype observed the mice and recorded the time interval between the injection of pentobarbital and the loss of righting reflex (LORR). At 2-min intervals, the animals were gently placed on their backs, and if they failed to right themselves, the time was noted. After the LORR, supplemental oxygen (4 l/min) was delivered through a nose cone placed near the snout. Mice that failed to lose their righting reflex were observed for at least 60 min. In addition, the corneal reflex was tested at 2-min intervals by lightly brushing the cornea with a 1.0 proline suture. The pineal reflex was tested using the suture to irritate

the lower aspect of the ear helix, and toe-pinch withdrawal was assessed by squeezing a hindlimb toe using a rubber-shod hemostat. Respiratory rate was measured during a 15-s interval every 2 min. Respiratory depression was defined as a $\geq$ 25% decrease in baseline respiratory rate determined before the injection. Finally, the time to the recovery of the righting reflex, or sleep time, was noted, and mice were observed for an additional 20 min before being returned to their cages. Animals were maintained under the heat lamp during the observation period. Two weeks to 1 month later, 15 (+/+) and 14 (−/−) mice from this initial group were injected with pentobarbital 35 mg/kg intraperitoneally and observed according to the protocol described.

In eight additional animals, the body temperature was measured by inserting a rectal probe (Fisher Scientific, Hampton, NH) immediately after pentobarbital 30 mg/kg was administered intraperitoneally. Temperature was measured at 2-min intervals until the animals regained the righting reflex or until 15 min had elapsed for mice that did not lose this reflex.

All animal study protocols were approved by the animal facility at the Samuel Lunenfeld Research Centre, Mount Sinai Hospital, Toronto, and the Animal Care Committee of the University of Toronto.

Plasma Pentobarbital Levels

The plasma concentration of pentobarbital was measured in six subjects consisting of three (+/+) mice and three (−/−) mice that had not been previously injected with the barbiturate. Animals were killed by decapitation 5 min after the injection of pentobarbital (30 mg/kg intraperitoneally). The sample was obtained at 5 min because this time approximates the latency to LORR in the (−/−) mice. Approximately 1 ml blood was collected from the decapitation site into a 1.5-ml microcentrifuge tube. Samples were centrifuged, and pentobarbital concentrations were assayed from the plasma using high-performance liquid chromatography.

Acute Isolation of Hippocampal Neurons

Mice older than 6 weeks of age were anesthetized with halothane and then decapitated. The entire brain was then rapidly removed and rinsed in cold (4°C) extracellular solution consisting of (in mM): NaCl 140, $CaCl_2$ 1.3, KCl 5.4, *N*-2-hydroxy-ethylpiperazine-*N*′-2-ethanesulphonic acid (HEPES) 25, glucose 33, and tetrodotoxin 0.0003. This solution was buffered to a *p*H of 7.4 with NaOH, and osmolality was adjusted to 320 to 325 mOsm. The hippocampi were then isolated and cut by hand with a razor blade into approximately 500-μm-thick slices. The slices were incubated in extracellular solution containing 0.4 mg/ml papain latex (Sigma Chemical Co., St. Louis, MO) for 15–30 min at room temperature (20–22°C), then washed in papain-free solution and allowed to acclimate while submersed in oxygenated extracellular solution at room temperature for 2 h. Each slice was transferred to a plastic 35-mm tissue culture dish (Nalge Nunc International, Roskilde, Denmark) before the isolation of individual pyramidal neurons. Pyramidal neurons from the CA1 region of the hippocampus were isolated by mechanical trituration using three Pasteur pipettes with consecutively smaller tip diameters (700 to 150 μm). The acutely dissociated hippocampal neurons were allowed to settle to the bottom of the dish before the recordings were made.

The genotypes of all mice used in these studies were confirmed by Southern blotting or polymerase chain reaction of tail genomic DNA.

Whole-Cell Recordings

All electrophysiologic studies were performed at room temperature (22°C). Patch electrodes were pulled from thin-walled borosilicate glass (1.5-mm outer diameter; World Precision Instruments, Sarasota, FL) using a two-stage vertical puller (Narishige PP-83, Tokyo, Japan) to a series resistance of 3–10 MΩ. The electrodes were filled with intracellular solution consisting of (in mM): CsF 140, CsOH 35, HEPES 10, $MgCl_2$ 2, EGTA 11, tetraethylammonium chloride 2, $CaCl_2$ 1, magnesium adenosine 5′-triphosphate 4. This solution was buffered to a *p*H of 7.4 using CsOH, and the osmolality was adjusted to 300–310 mOsm. For the experiments in which GABA was applied as the agonist, the recording solution contained CsF 70 mM and CsCl 60 mM instead of CsF 140 mM. The CsCl was added to increase intracellular chloride (Cl^-) concentrations so that a detectable outward current could be recorded after the application of GABA.

Acutely isolated neurons were voltage clamped at a holding potential of −60 mV. Whole-cell currents were recorded using the Axopatch 1D amplifier (Axon Instruments Inc., Foster City, CA) and data were filtered (2 kHz), digitized, and acquired on-line using the pCLAMP5 program (Axon Instruments). Changes in series resistance were monitored during the recordings by measuring the capacitance transient resulting from a hyperpolarizing test pulse of 10 mV. Recordings that demonstrated marked changes in access resistance were not used for data analysis.

A multibarrel perfusion system[21] was used to achieve a rapid exchange (30 ms) of the extracellular solution. Three square capillary tubes (400 μM × 400 μM) were glued together and mounted on a Leitz manipulator (Wild Leitz Canada Ltd., Midland, Ontario, Canada). Each barrel was connected to a 7-ml reservoir of perfusion fluid, and the flow rate set to approximately 0.5 ml/min by adjusting the height of the reservoir. A computer-driven motor-based stepper (Vexta motor; Oriental Motor Co., Torrance, CA) was used to laterally move the capillary assembly. After the formation of the whole-cell configuration, neurons were lifted into the outflow of the barrels. Cells were perfused with the extracellular solution or solutions containing the AMPA receptor agonist, kainate (Sigma Chemical Co.), GABA (Sigma Chemical Co.), or barbiturates (pentobarbital, thiopental, and phenobarbital).

Glutamate-evoked currents mediated by AMPA receptors rapidly desensitize to a low steady-state amplitude. Although kainate-evoked currents also desensitize, the extent of desensitization is considerably less, and the steady-state current is greater compared with glutamate-evoked responses.[22] Therefore, kainate was used to investigate the inhibition of AMPA receptors by barbiturates as previously described.[19,20,23,24] Various concentrations of barbiturates were applied during the steady-state response evoked by kainate. It is unlikely that the activation of kainate receptors, which undergo a fast pronounced desensitization,[25] contributes appreciably to the currents recorded in these experiments. Because it is the endogenous ligand of AMPA receptors, glutamate (3 mM) was applied to activate AMPA receptors in another set of experiments. This saturating concentration of glutamate was applied with the *N*-methyl-D-aspartate receptor antagonist, DL-2-amino-5-phophonovaleric acid (40 μM; Sigma Chemical Co.), and $MgCl_2$ 2 mM in the absence and presence of pentobarbital 30 μM and 100 μM. For these experiments, bicuculline 20 μM was added to all solutions to inhibit barbiturate activated Cl^- current mediated by $GABA_A$ receptors.

The current amplitude was measured using pCLAMP (Axon Instruments), and data were plotted using GraphPad Prism (Graph Pad, San Diego, CA). Concentration-response relationships for kainate-evoked currents and GABA-evoked currents recorded in the presence and absence of pentobarbital 30 μM were fitted using a modified version of the Michaelis-Menten equation by the least squares method. The concentration of kainate that produced 50% of the maximal response (EC_{50}) and the Hill coefficient (n_H) were determined according to the equation:

$$I = I_{max} \times 1/(1 + (EC_{50}/[ligand])^{nH})$$

where I_{max} is the maximal response observed at a saturating concentration of the agonist. Membrane capacitance, as an approximation of neuron size, was estimated from the area under the capacitance transient evoked by a 10-mV hyperpolarizing pulse applied after the formation of the whole-cell configuration.

For concentration–inhibition analysis, kainate was applied at the EC_{55-60} concentration in the absence or presence of the barbiturates. The concentrations of pentobarbital, thiopental, or phenobarbital that produced 50% of the maximal inhibition (IC_{50}) were determined from the concentration–inhibition curves. Data points were normalized to the maximal inhibition and fit according to the equation:

$$I = I_{max} \times 1/(1 + (IC_{50}/[\text{noncompetitive antagonist}])^{nH})$$

where I_{max} is the maximal inhibition produced by a saturating concentration of the antagonist.

GABA and glutamate responses recorded in the presence of pentobarbital were examined for changes in amplitude of the peak and steady-state currents, respectively.

Statistical Analysis

All results were reported as mean ± SEM unless otherwise indicated. For the behavioral study, the latency to LORR and sleep time were compared between groups using a one-way analysis of variance (SigmaStat 2.0 software; SPSS Inc., San Rafael, CA). The chi-square and Fisher exact tests were used to compare the number of mice in each group that showed the loss of the righting, corneal, pineal, and toe-pinch withdrawal reflexes. Where appropriate, the EC_{50} values for kainate and GABA-evoked currents, as well as the IC_{50} values for pentobarbital, thiopental, and phenobarbital for (+/+) and (−/−) neurons were compared using the Student *t* test. Data sets for which tests of normality failed were analyzed with corresponding nonparametric tests.

Results

Anaesthetic Sensitivity to Pentobarbital Increased in GluR2 *Null Mutant Mice*

The study population of (+/+) and (−/−) mice were initially organized into three groups according to post-

Table 1. Demographics of Behavioral Study

	Group 1 (+/+) (n = 28)	Group 2 (+/+) (n = 8)	Group 3 (+/+) (n = 9)	Group 1 (+/−) (n = 26)	Group 1 (−/−) (n = 13)	Group 2 (−/−) (n = 8)	Group 3 (−/−) (n = 7)
Age (wk)	7.9 ± 0.3	24.3 ± 0.6	54.6 ± 1.4	7.7 ± 0.3	9.4 ± 0.5	22.8 ± 0.1	55.8 ± 1.8
Weight (g)	28.7 ± 0.9	35.1 ± 2.4	35.6 ± 1.6	29.2 ± 0.9	27.9 ± 0.7	31.7 ± 0.6	35.8 ± 2.5

natal age: group 1 (5–10 weeks), group 2 (23 weeks), and group 3 (50 weeks). No significant differences in weight were observed between the age-matched groups (table 1). Similarly, no age-dependent differences were demonstrated for the latency to LORR, sleep time, or loss of corneal or pineal reflexes within each genotype. Therefore, the results were pooled according to the genotype for all ages.

After intraperitoneal injection of pentobarbital 30 mg/kg, a greater proportion of the (−/−) mice demonstrated LORR (table 2) and a shorter latency to LORR (5.1 ± 0.5 min, n = 26; 6.5 ± 0.4 min, n = 17; 7.8 ± 0.9, n = 25; $P < 0.05$) compared with (+/−) or (+/+) littermates, respectively (fig. 1A). *GluR2* null mutant mice also demonstrated a longer sleep time (18.1 ± 1.5 *vs.* 10.3 ± 1.3 and 10.8 ± 1.5 min; $P < 0.05$; fig. 1B). A greater proportion of (−/−) mice lost their corneal and pineal reflexes compared with the (+/+) and (+/−) mice ($P < 0.05$; table 2). Loss of the toe-pinch withdrawal reflex was not demonstrated in any of the mice after injection of pentobarbital. The enhanced sensitivity to pentobarbital in (−/−) mice was not likely attributed to pharmacokinetic factors because the plasma concentration of pentobarbital was similar, at least at the 5-min interval, in (−/−) mice and (+/+) littermates (128.8 ± 15.9 μM, n = 3 *vs.* 113.3 ± 12.8 μM, n = 3, respectively; $P > 0.05$).

Some of the mice that were not killed for the electrophysiologic studies were allowed to recover for a minimum 2-week period. Pentobarbital 35 mg/kg was administered intraperitoneally as previously described. Three mice, two (−/−) and one (+/+), died from respiratory failure, whereas 14 (+/+) and 12 (−/−) mice were successfully anesthetized, and most of the subjects demonstrated LORR (table 3). Consistent with our previous findings, the (−/−) mice showed a decreased time to LORR (4.1 ± 0.4 min, n = 12 *vs.* 5.7 ± 0.3 min, n = 13; $P < 0.05$) and increased sleep time (24.5 ± 3.5 min, n = 12 *vs.* 12.6 ± 2.8 min, n = 12; $P < 0.05$). A greater proportion of (−/−) mice lost their pineal and corneal reflexes compared with (+/+) littermates; however, these differences were not statistically significant (table 3). The incidence of respiratory depression was not different between the (+/+) and (−/−) mice (tables 2 and 3).

Because the sensitivity to anesthetics can be influenced by core temperature, eight additional mice were observed for changes in rectal temperature after pentobarbital 30 mg/kg was administered intraperitoneally. No significant differences in temperature was detected at any time after the pentobarbital injection, including at 4 min [37.0 ± 0.4°C (+/+), n = 4 *vs.* 36.5 ± 0.4°C (−/−), n = 4] and 10 min [37.3 ± 0.2°C (+/+), n = 4 *vs.* 36.8 ± 0.3°C (−/−), n = 4].

In summary, these results demonstrate an increased anesthetic sensitivity to pentobarbital in the (−/−) mice compared with (+/−) and (+/+) littermates as evidence by a shorter latency to LORR, longer sleep time, and the greater proportion of mice that lost the corneal and pineal reflexes. This enhanced sensitivity could not be attributed to differences in blood concentrations or changes in rectal temperature.

Potency of Kainate Is Increased in GluR2*-Deficient AMPA Receptors*

The subunit composition of ligand-gated receptors influences the EC_{50} value of the receptor for agonist, as well as their sensitivity to pharmacologic agents. Furthermore, the extent of inhibition produced by an antagonist can vary with the concentration of agonist. Therefore, to ensure that equi-effective concentrations of agonist were used to elicit control currents in (−/−)

Table 2. Behavioral Study Results after Pentobarbital 30 mg/kg Intraperitoneally

	+/+ (n = 45)	+/− (n = 26)	−/− (n = 28)
Number (%) of mice with loss of righting reflex	25 (56)	17 (65)	26 (93)*
Number (%) of mice with loss of corneal reflex	28 (62)	17 (65)	25 (89)*
Number (%) of mice with loss of pineal reflex	8 (18)	10 (38)	18 (64)*
Number (%) of mice with respiratory depression	27 (60)	15 (58)	17 (61)

* Significantly different from (+/+) mice ($P < 0.05$, using the chi-square test).

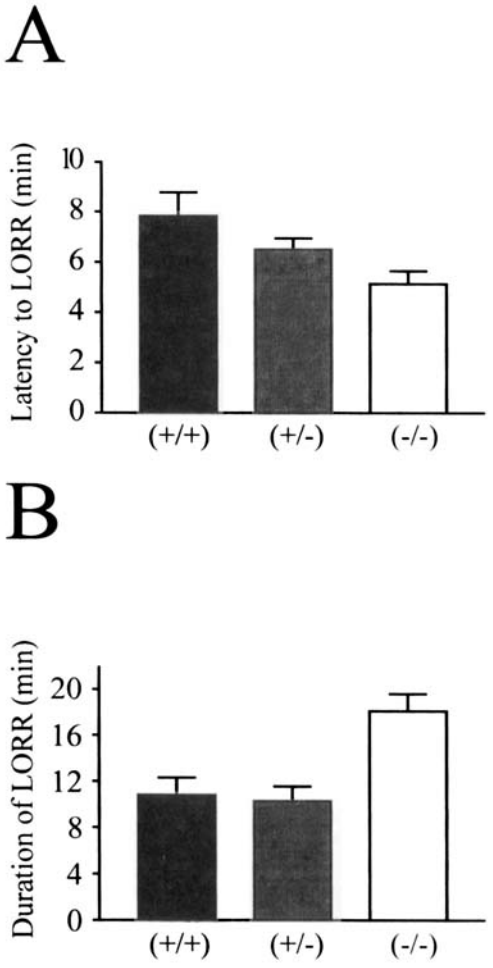

Fig. 1. Loss of righting reflex measurements after intraperitoneal administration of 30 mg/kg pentobarbital to wild-type (+/+), heterozygous (+/−), and mutant (−/−) mice. (*A*) Latency to the loss of righting reflex was shorter in the (−/−) mice (5.1 ± 0.5 min, n = 26) compared with the (+/−) and (+/+) mice (6.5 ± 0.4 min, n = 17, and 7.8 ± 0.9, n = 25, respectively; $P < 0.05$). (*B*) Similarly, the duration of the loss of righting reflex (sleep time) was longer in the (−/−) mice compared with (+/−) and (+/+) littermates (18.1 ± 1.5 *vs.* 10.3 ± 1.3 and 10.8 ± 1.5 min, respectively; $P < 0.05$).

and (+/+) neurons, the concentration-response relationships for kainate-evoked currents were first examined.

Applications of kainate (> 10 μM) activated an inward current in all hippocampal neurons tested. The maximum current evoked by a saturating concentration of kainate (I_{max}) was not influenced by the presence of the *GluR2* subunit: (−/−)I_{max} = 1,341 ± 217 pA, n = 15 *versus* (+/+)I_{max} = 1,746 ± 233 pA, n = 12 ($P > 0.05$). Similarly, no differences were observed in the membrane capacitance in the dissociated cells: (−/−) 14.2 ± 3.9 pF *versus* (+/+) 14.9 ± 3.8 pF. The concentration-response relationship indicated the EC_{50} value for kainate-evoked current was significantly lower for (−/−) neurons compared with (+/+) neurons (136 ± 7 μM, n = 17 *vs.* 226 ± 23 μM, n = 15; $P < 0.05$), respectively. Our results are consistent with previous reports of a higher potency for kainate in recombinant AMPA receptors that lack the *GluR2* subunit.[26] The EC_{50} values for receptors containing the $GluR2_{flip}$ subunit in combination with *GluR1* (EC_{50} = 110 μM) or $GluR1/GluR3_{flip}$ (EC_{50}, 100 μM) were greater than those values for homomeric *GluR1* (EC_{50}, 32 μM) or dimeric $GluR1/GluR3_{flip}$ (EC_{50}, 55 μM) receptors. The EC_{50} value we report for (+/+) neurons (EC_{50}, 226 μM) approximate those values reported for pyramidal neurons isolated from the CA3 region (EC_{50}, 344 μM) or CA1 region (EC_{50}, 474 μM) of the rat hippocampus.[27] In addition, the Hill coefficient (1.69 ± 0.04 *vs.* 2.06 ± 0.13; $P < 0.05$) was lower for (−/−) neurons compared with (+/+) neurons, respectively (fig. 2), suggesting a decreased cooperativity for kainate activation of *GluR2*-deficient AMPA receptors.[28]

Inhibition of AMPA Receptors by Barbiturates in GluR2-*Deficient and Wild-type Neurons*

To investigate the effects of barbiturates on AMPA receptors, equi-effective concentrations of kainate were applied to (−/−) neurons (EC_{55}, 150 μM) or (+/+) neurons (EC_{60}, 300 μM). Kainate was applied for 1.5 s before the application of the various concentrations of barbiturates. Only recordings that demonstrated a stable level of inhibition and full recovery after washout of the barbiturate were used for the data analysis.

The concentration-inhibition relationship for pentobarbital blockade of kainate-evoked currents is illustrated in figures 3 and 4A. The IC_{50} value for pento-

Table 3. Behavioral Study Results after Pentobarbital 35 mg/kg Intraperitoneally

	+/+ (n = 14)	−/− (n = 12)
Number (%) of mice with loss of righting reflex	13 (93)	12 (100)
Number (%) of mice with loss of corneal reflex	11 (79)	12 (100)
Number (%) of mice with loss of pineal reflex	3 (21)	7 (58)
Number (%) of mice with respiratory depression	12 (86)	8 (67)

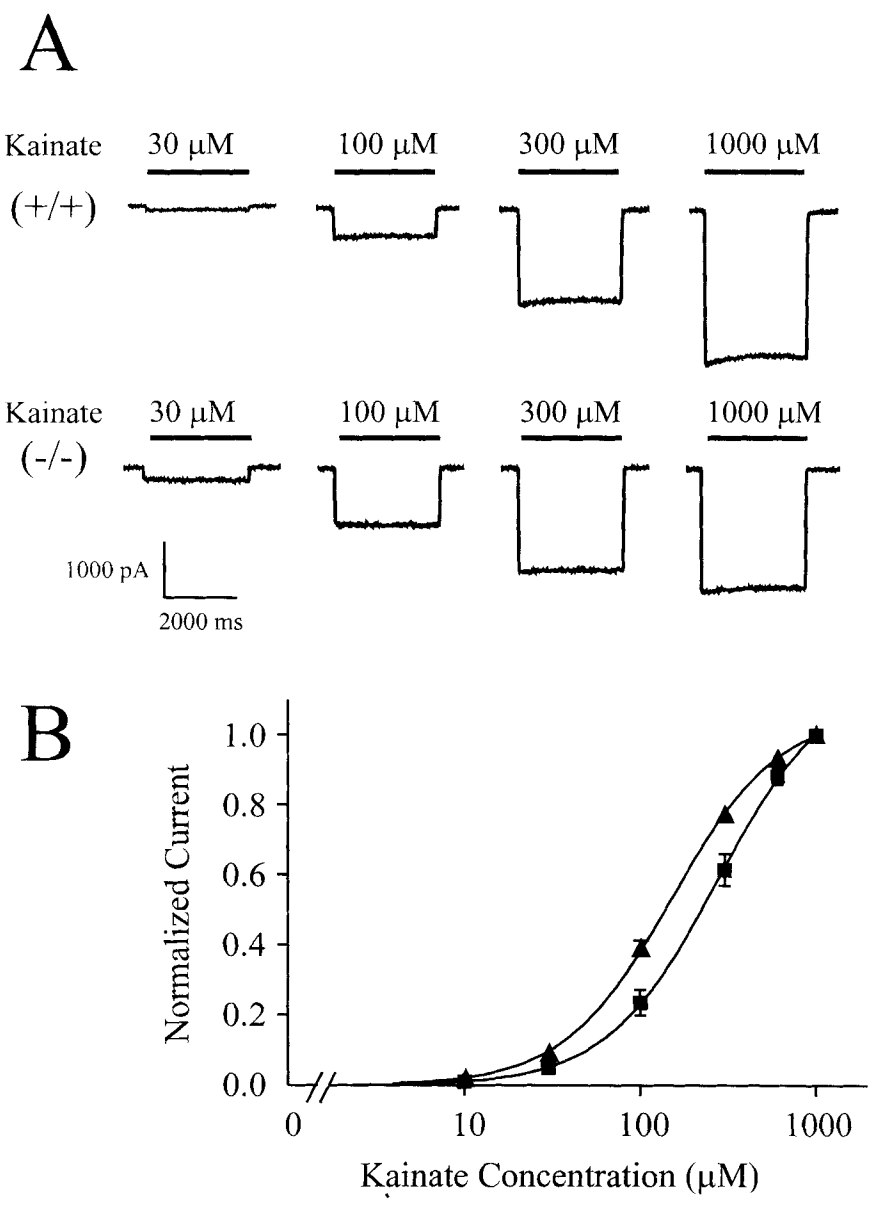

Fig. 2. Kainate-activated currents in acutely isolated hippocampal pyramidal neurons from wild-type (+/+) and mutant (−/−) mice. (*A*) Representative kainate-evoked currents at subsaturating (30, 100, and 300 μM) and saturating (1,000 μM) concentrations are shown. (*B*) Concentration–response curves for kainate-evoked currents in (+/+) neurons (*squares*), and (−/−) neurons (*triangles*) were constructed by normalizing to the maximal response and fitting the data points using the modified Michaelis-Menton equation. The concentrations that activated 50% of the maximal current (EC_{50}) and Hill coefficients (n_H) were: (+/+) EC_{50}, 226 ± 23 μM (n = 15); (−/−) EC_{50}, 136 ± 7 μM (n = 17); (+/+) n_H, 2.06 ± 0.13; and (−/−) n_H, 1.69 ± 0.04.

barbital inhibition was approximately sixfold greater for (−/−) neurons compared with (+/+) neurons (301 ± 52 μM *vs.* 51 ± 10 μM; $P < 0.05$). Similarly, the IC_{50} values for thiopental (153 ± 29 μM *vs.* 34 ± 6 μM; $P < 0.05$) and phenobarbital (930 ± 344 μM *vs.* 205 ± 55 μM; $P < 0.05$) were fourfold to fivefold greater in (−/−) compared with (+/+) neurons, respectively (figs. 4B and 4C). These results demonstrate a reduced barbiturate sensitivity of AMPA receptors in *GluR2*-deficient neurons. No significant differences in the Hill coefficient (n_H) were observed for pentobarbital [(+/+) n_H = 1.00 ± 0.03 and (−/−) n_H = 1.31 ± 0.27] and thiopental [(+/+) n_H = 1.08 ± 0.05 and (−/−) n_H = 0.98 ± 0.16]. However, the Hill coefficient for phenobarbital was increased in the (−/−) neurons: (+/+) n_H = 1.12 ± 0.07 and (−/−) n_H = 1.63 ± 0.18 ($P < 0.05$). The reduction in the slope factor for barbiturate concentration-inhibition curves reported for recombinant *GluR2*-deficient receptors[19] was not demonstrated in (−/−) neurons.

Consistent with these results, the steady-state current evoked by glutamate (3 mM) was also sensitive to inhi-

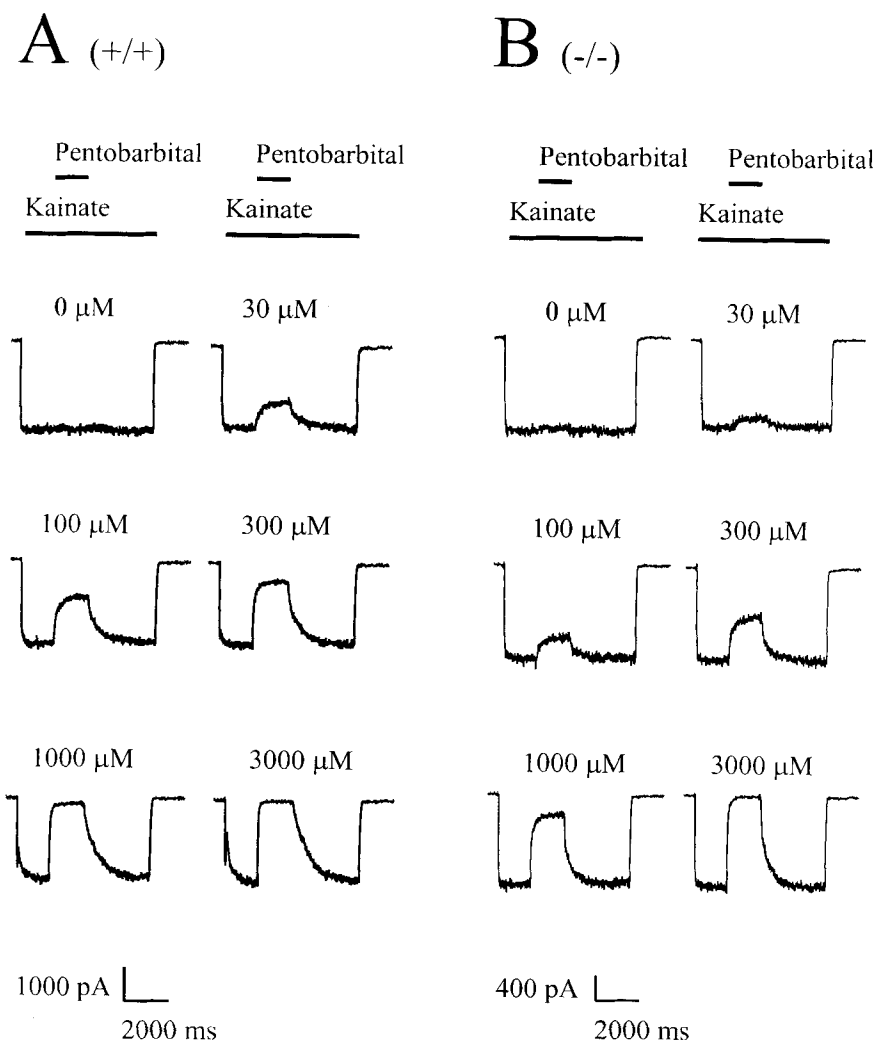

Fig. 3. Inhibition of kainate-evoked currents by pentobarbital. The application of various concentrations of pentobarbital (0, 30, 100, 300, 1,000, and 3,000 μM) are shown for current activated by 300 μM kainate in (*A*) wild-type (+/+) neurons and by 150 μM kainate in (*B*) mutant (−/−) neurons. Kainate was applied as indicated by the solid bar before, during, and after the application of pentobarbital.

bition by pentobarbital. Pentobarbital 30 μM and 100 μM caused a significant inhibition of the current recorded from (+/+) neurons (30% ± 7% and 49% ± 6%, respectively; n = 11; $P < 0.05$) but not from (−/−) neurons (8% ± 11% and 24% ± 12%; n = 4; $P = 0.40$ and 0.26, respectively). Therefore, a decrease in barbiturate inhibition of AMPA receptors in (−/−) neurons was also demonstrated when the endogenous ligand, glutamate, was used to activate AMPA receptors.

Potentiation of $GABA_A$ Receptors by Barbiturates is Unchanged in GluR2*-deficient Neurons*

The $GABA_A$ receptor is thought to be a primary site of action of barbiturates.[29] Therefore, we also investigated the effects of pentobarbital (30 μM) on $GABA_A$ receptor-mediated current activated by a subsaturating (30 μM) and a saturating concentration of GABA (600 μM). No differences were observed in the maximal amplitude of currents evoked by GABA 30 μM recorded from (−/−) neurons (1,489 ± 345 pA, n = 10) or (+/+) neurons (1,160 ± 235 pA, n = 13), respectively. Similarly, no difference in the maximal current activated by GABA 600 μM was apparent for responses from (−/−) neurons (4,654 ± 612 pA, n = 12) and (+/+) neurons (4,205 ± 695 pA, n = 12). Pentobarbital (30 μM) applied in the absence of GABA did not activate inward current in any of the neurons. However, pentobarbital (30 μM) potentiated the peak currents evoked by 30 μM GABA but not 600 μM GABA (fig. 5). The effects of pentobarbital on the GABA concentration-response relationship were also investigated. The calculated EC_{50} values for GABA were: (−/−), 51 ± 6 μM (n = 17); and (+/+), 46 ± 6 μM (n =

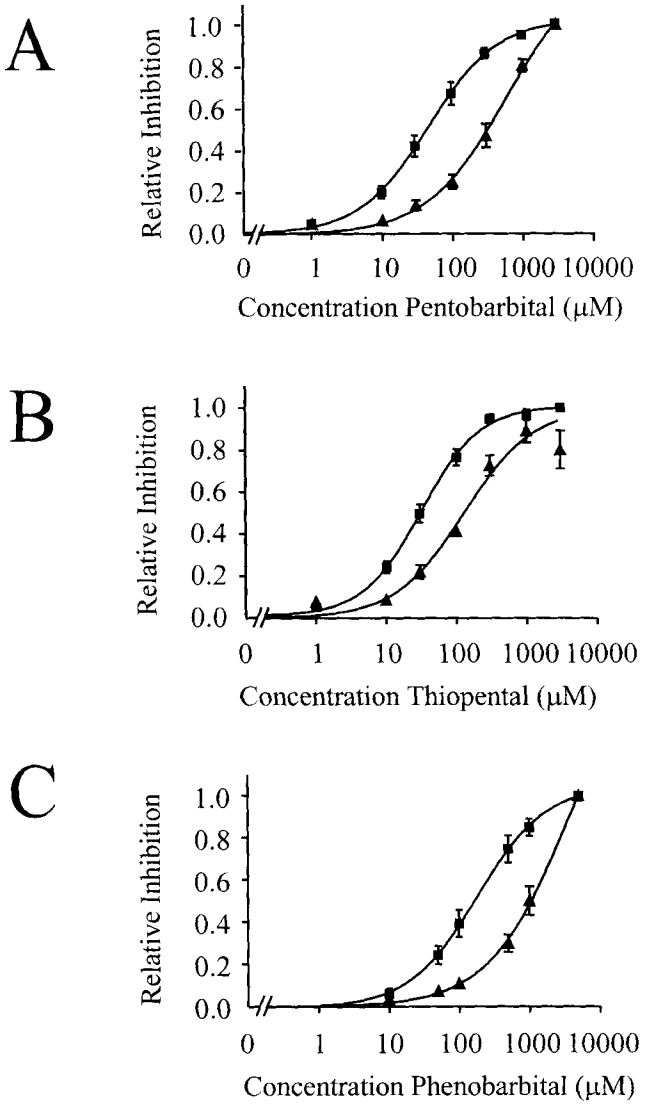

Fig. 4. Concentration–inhibition curves for barbiturate modulation of AMPA receptors in mutant (−/−) and wild-type (+/+) neurons. The concentrations ranged from 10 to 3,000 μM of (*A*) pentobarbital, (*B*) thiopental, and (*C*) phenobarbital in (+/+) (*squares*) and (−/−) (*triangles*) neurons. The IC_{50} values for each barbiturate and Hill coefficients (n_H) were determined by fitting the curves to a standard Hill equation. Pentobarbital IC_{50}: (+/+), 51 ± 10 μM (n = 7); (−/−), 301 ± 52 μM (n = 10). n_H: (+/+), 1.00 ± 0.03; (−/−), 1.31 ± 0.27. Thiopental IC_{50}: (+/+), 34 ± 5 μM (n = 6); (−/−), 153 ± 29 μM (n = 5). n_H: (+/+), 1.08 ± 0.05; (−/−), 0.98 ± 0.16. And phenobarbital IC_{50}: (+/+), 205 ± 55 μM (n = 7); (−/−), 930 ± 130 μM (n = 7). n_H: (+/+), 1.12 ± 0.07; (−/−); 1.63 ± 0.18.

13). Pentobarbital caused a shift to the left of the GABA concentration-response curve and significantly reduced the GABA EC_{50} value to 43 ± 6 μM (n = 11) and 34 ± 5 μM (n = 11) for (−/−) and (+/+) neurons, respectively (fig. 6). These results indicate that $GABA_A$ receptors present in (−/−) and (+/+) neurons are similarly influenced by pentobarbital.

Discussion

Our results show that *GluR2* null mutant mice are more sensitive to the anesthetic effects of pentobarbital compared with wild-type littermates. In contrast, AMPA receptors in *GluR2*-deficient neurons were resistant to inhibition by barbiturates as indicated by a fourfold to sixfold increase in the IC_{50} values for pentobarbital, thiopental, and phenobarbital. Taken together, these data demonstrate that the behavioral effects of barbiturates do not correlate with the inhibition of AMPA receptors in this mouse model. Although the rank order of potencies of the barbiturates for AMPA receptor inhibition (thiopental > pentobarbital > phenobarbital) is consistent with the behavioral potencies in animals and humans,[30] this rank order also correlates with the modulation of $GABA_A$ receptors, a primary target site for anesthetic drugs.

Previous behavioral studies suggest that inhibition of AMPA receptors contributes to the neurodepressive effects of barbiturates. The selective non-*N*-methyl-D-aspartate receptor antagonist, NBQX, administered intravenously in rats caused a dose-dependent increase in the duration of LORR caused by hexobarbital.[31] Potentiation of the anesthetic effect of hexobarbital by NBQX, together with evidence that barbiturates inhibit the AMPA receptor *in vitro*, led to the suggestion that AMPA receptors contribute to the clinical properties of barbiturates. Alternatively, these behavioral data could also be interpreted as indicating that NBQX reduced the baseline level of excitatory neurotransmission, rendering the central nervous system more sensitive to the inhibitory GABAergic effects of barbiturates.

Electrophysiologic studies support a reduction in excitatory synaptic signaling in *GluR2* null mutant mice as the amplitude of excitatory postsynaptic potentials and currents are reduced in hippocampal slices from these mice.[13] This suggests that the absence of the *GluR2* subunit is associated with a generalized reduction in excitatory neurotransmission, a state analogous to that induced by low concentrations of NBQX. Consequently, barbiturates may unmask an inherent susceptibility to neurodepressive drugs.

An alternative mechanism to account for the enhanced sensitivity to pentobarbital in *GluR2* null mu-

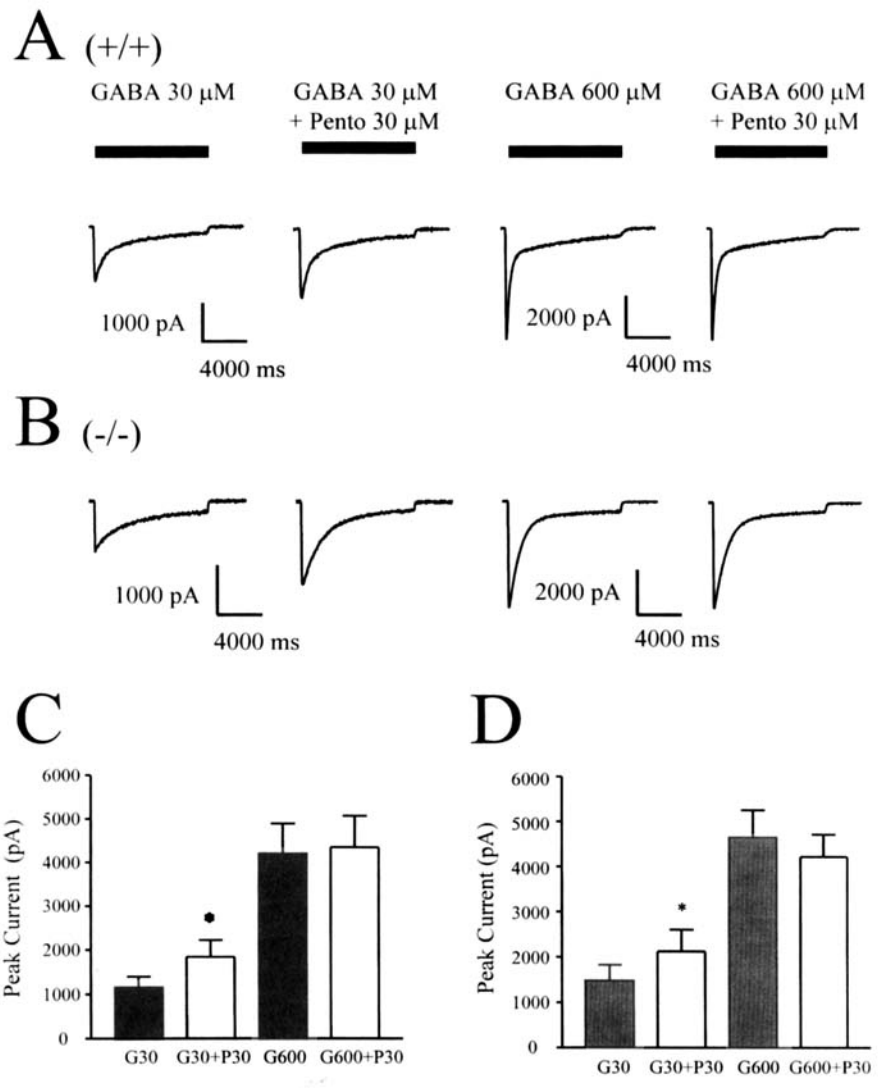

Fig. 5. Peak current responses to submaximal (30 μM) and maximal (600 μM) concentrations of GABA in the absence and presence of 30 μM pentobarbital in (*A*) wild-type (+/+) and (*B*) mutant (−/−) acutely dissociated hippocampal pyramidal neurons. The peak current responses to 30 μM and 600 μM GABA were similar in (*C*) (+/+) neurons (1,160 ± 235 pA [n = 13] and 4,205 ± 695 pA [n = 12]) and (*D*) (−/−) neurons (1,489 ± 345 pA [n = 10] and 4,654 ± 612 pA [n = 12]; *P* = 0.52 and 0.61, respectively). No difference was observed in the enhancement by pentobarbital (30 μM) of the peak current evoked by these submaximal and maximal concentrations of GABA between the (+/+) neurons (1,845 ± 387 pA [n = 13] and 4,357 ± 722 pA [n = 12], respectively) and (−/−) neurons (2,135 ± 479 pA [n = 10] and 4,231 ± 496 pA [n = 12], respectively).

tant mice is attributed to the modulation of polyneuronal networks. For example, in hippocampal circuits, inhibitory GABAergic interneurons are activated by glutamate. AMPA receptors present in these interneurons can contain *GluR2* subunits as indicated by *in situ* hybridization and immunofluorescence labeling studies.[32,33] In wild-type mice, pentobarbital blockade of AMPA receptors would reduce the activation of inhibitory interneurons, thereby reducing GABAergic transmission in these mice. In contrast, in *GluR2* null mutant mice, barbiturate-resistant AMPA receptors would permit the persistent activation of inhibitory interneurons.

Thus, two mechanisms are postulated to account for our experimental results. The first attributes the enhanced sensitivity in *GluR2* null mutant mice to a global reduction of excitatory neurotransmission and suggests that barbiturates act at non-AMPA receptors (such as $GABA_A$ receptors). The second mechanism attributes the increased sensitivity in *GluR2* null mutant mice to barbiturate-resistant AMPA receptors that activate inhibitory interneurons. Anesthetics that cause minimal inhibition of AMPA receptors and cause no differential modulation of wild-type and *GluR2*-deficient receptors could be used to distinguish between these two possibilities. We predict that if excitatory neurotransmission is globally reduced in *GluR2* null mutant mice, then AMPA receptor-independent anesthetics[34] would also be more po-

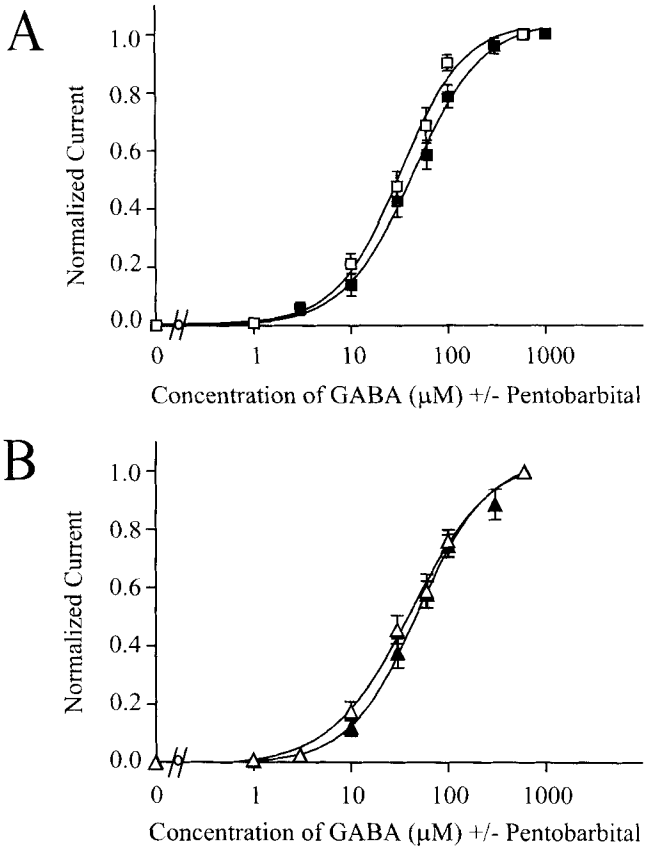

Fig. 6. Concentration–response relationships for GABA and GABA with 30 μM pentobarbital-evoked currents recorded in acutely dissociated hippocampal pyramidal neurons. The peak current responses to GABA at 1, 3, 10, 30, 100, 300, 600, and 1,000 μM in the absence and presence of pentobarbital 30 μM were normalized to the maximal response in (*A*) wild-type (+/+) (*filled squares*, GABA; *open squares*, GABA plus pentobarbital) and (*B*) mutant (−/−) neurons (*filled triangles*, GABA; *open triangles*, GABA plus pentobarbital). The EC_{50} values for GABA and GABA with 30 μM pentobarbital and the Hill coefficients (n_H) were determined by fitting the curves to a standard Hill equation. The GABA EC_{50} value in the (+/+) neurons was similar to that in the (−/−) neurons (EC_{50} = 46 ± 6 μM, n_H = 1.60 ± 0.07 [n = 13], and EC_{50} = 51 ± 6 μM, n_H = 1.66 ± 0.06 [n = 17], respectively; *P* = 0.51). Importantly, the EC_{50} values for GABA plus pentobarbital were not different in the (+/+) neurons (EC_{50} = 34 ± 5 μM, n_H = 1.61 ± 0.06; n = 11) and (−/−) neurons (EC_{50} = 43 ± 6 μM, n_H = 1.58 ± 0.07; n = 11; *P* = 0.25).

tent in these mice. In this regard, the volatile anesthetic halothane causes minimal inhibition of AMPA receptors at clinically relevant concentrations.[35] Preliminary studies indicate that halothane is more potent in *GluR2* null mutant compared with wild-type mice for LORR,[36] supporting the model in which the increased anesthetic sensitivity is attributed to a reduction in glutamate-mediated excitatory neurotransmission.

Subtle but important differences in the number or function of synaptic AMPA receptors present in *GluR2* null mutant and wild-type mice may not be revealed by analyzing kainate-evoked currents recorded from the soma of acutely dissociated neurons. Although we demonstrated that the potency of AMPA receptors for kainate is lower in wild-type (EC_{50}, 226 μM) compared with *GluR2*-deficient receptors (EC_{50}, 136 μM), we observed no difference in the maximal amplitude of kainate-evoked currents in *GluR2*-deficient and wild-type neurons. This result is consistent with the findings of Feldmeyer *et al.*,[14] who reported that the maximal macroscopic conductance to kainate was similar for wild-type and *GluR2*-deficient ($GluR^{neo/neo}$) neurons. However, the *GluR2* subunit plays a critical role in the surface expression and trafficking of glutamate receptors to the postsynaptic compartment.[37] A reduction in the number or function of synaptic AMPA receptors in *GluR2*-deficient neurons could contribute to the reduction in excitatory field potentials and increased sensitivity to anesthetics.

Resistance of *GluR2*-deficient receptors to barbiturate inhibition was first demonstrated in recombinant AMPA receptor subunits (*GluR1* to *GluR4*) expressed in *Xenopus* oocytes. Pentobarbital inhibited *GluR2*-containing receptors (*GluR1/2* or *GluR2/3*) with an IC_{50} of approximately 180–200 μM, whereas *GluR2*-deficient receptors (*GluR1*, *GluR1/3*, *GluR3*) had IC_{50} values of 1.1–2 mM.[19] The absence of the *GluR2* subunit was also associated with a decrease in the slope of the concentration–inhibition curve and a Hill coefficient less than 1. These results indicate that the absence of the *GluR2* subunit may cause a decrease in the number of drug binding sites or a change in the cooperativity or access to the binding site.[28] Our results in native neurons from *GluR2* mutant mice demonstrate a similar decrease in potency for barbiturate inhibition of *GluR2*-deficient receptors and a low value for the Hill coefficient. However, deciphering the molecular mechanism(s) of inhibition by analyzing the concentration–response relation in mutant receptors is problematic because differences in agonist binding or gating of AMPA receptors may not be revealed by the shape of the concentration–response curve. Further studies are necessary to clarify the mechanisms of barbiturate inhibition of AMPA receptors.

In summary, our behavioral study indicates that *GluR2* null mutant mice are more sensitive to barbiturates despite a reduced inhibition of *GluR2*-deficient AMPA re-

ceptors by barbiturates. Our behavioral experiments were primarily designed to measure LORR as a surrogate end point for the loss of consciousness. However, the state of general anesthesia is comprised of multiple components, including hypnosis, amnesia, analgesia, and autonomic stability. Our results cannot be extrapolated to include the other components of general anesthesia such as analgesia or immobility in response to pain, because the absence or presence of the *GluR2* subunit might differentially influence these end points. Nevertheless, from a clinical perspective, our results are compelling because a variety of neurologic insults, including ischemia and epilepsy, are associated with the down-regulation of the *GluR2* subunit.[38] Our data predict that disorders associated with a relative reduction in *GluR2* subunit expression, including stroke,[39,40] schizophrenia,[41,42] Alzheimer's disease,[43] and amyotrophic lateral sclerosis,[44,45] would be associated with a decreased dose requirement for anesthetic drugs.

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