Hydroxyamide Analogs of Propofol Exhibit State-Dependent Block of Sodium Channels in Hippocampal Neurons: Implications for Anticonvulsant Activity

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ABSTRACT

Although propofol is most commonly known for its general anesthetic properties, at subanesthetic doses, propofol has been effectively used to suppress seizures during refractory status epilepticus, a mechanism, in part, attributed to the inhibition of neuronal sodium channels. In this study, we have designed and synthesized two novel analogs of propofol, HS245 [2-(3-ethyl-4-hydroxy-5-isopropyl-phenyl)-3,3,3-trifluoro-2-hydroxy-propionamide] and HS357 [2-hydroxy-8-(4-hydroxy-3,5-diisopropyl-phenyl)-2-trifluoromethyl-octanoic acid amide], and determined their effects on sodium currents recorded from cultured hippocampal neurons. HS357 had greater affinity for the inactivated state of the sodium channel than propofol and HS245 (0.22 versus 0.74 and 1.2 μM, respectively) and exhibited the greatest ratio of affinity for the resting over the inactivated state. HS357 also demonstrated greater use-dependent block and delayed recovery from inactivation in comparison with propofol and HS245. Under current-clamp conditions, action potentials from hippocampal CA1 neurons in slices were evoked by current injection, or following perfusion with a zero Mg2+/7 mM K+ artificial cerebrospinal fluid solution. Propofol and HS357 reduced the number of current-induced action potentials; however, HS357 caused a greater reduction in the number of spontaneous action potentials. Consistent with these electrophysiology studies, propofol and HS357 protected mice against acute seizures in the 6-Hz (22-mA) partial psychomotor model. Efficacious doses of propofol were associated with an impairment of motor coordination as assessed in the rotodex toxicity assay. In contrast, HS357 demonstrated a 2-fold greater protective index than propofol. Thus, propofol analogs represent an important structural class from which not only effective, but also safer, anticonvulsants may be developed.

Epilepsy is a neurological disorder that affects approximately 1 to 2% of the population. Treatment of epilepsy focuses on the suppression of seizures via the use of antiepileptic drugs (AEDs) (Brownie and Holmes, 2001). First generation AEDs, such as phenytoin, carbamazepine, phenobarbital, and sodium valproate, along with second generation AEDs, such as topiramate, gabapentin, lamotrigine, and zonisamide, offer a wide selection of possible therapeutic treatments for suppression of seizures. Although the number of AEDs has increased, the percentage of patients who fail to be treated successfully remains constant at an alarming 30% (Loscher and Schmidt, 2002). Substantial problems exist with toxicity, resistance, and idiosyncratic reactions in a number of the currently used AEDs (Brodie, 2001), all of which likely contribute to their failure rate. In view of this failure rate, there remains a need for a better understanding of the mechanisms involved in suppression of epileptic seizures with minimal side effects.

Voltage-gated sodium channels play an important role in determining neuronal excitability and, therefore, constitute a proven target for the suppression of epileptic seizures. Sodium channels consist of a pore-forming α subunit and auxiliary β subunits, which modulate the gating kinetics of the

ABBREVIATIONS: AED, antiepileptic drug; AP, action potential; HS245, 2-(3-ethyl-4-hydroxy-5-isopropyl-phenyl)-3,3,3-trifluoro-2-hydroxy-propionamide; HS357, 2-hydroxy-8-(4-hydroxy-3,5-diisopropyl-phenyl)-2-trifluoromethyl-octanoic acid amide; ACSF, artificial cerebrospinal fluid; DMSO, dimethyl sulfoxide; ANOVA, analysis of variance; TPE, time of peak effect; PI, protective index.
Propofol (2,6-diosopropylphenol) is most commonly known for its use as an i.v. general anesthetic; however, at subanesthetic doses, propofol is used clinically during refractory status epilepticus, a critical medical emergency with mortality rates as high as 76% in elderly patients (Prasad et al., 2001; Claassen et al., 2002; Marik and Varon, 2004; Rossetti et al., 2004). Propofol has been shown to inhibit sodium currents in mammalian cell lines expressing rat Na$_{1.2}$ (Rehberg and Duch, 1999), to activate GABA currents in hippocampal neurons (Orser et al., 1994), and to inhibit L-type calcium currents in cortical neurons (Martella et al., 2005). However, its modulation of sodium currents (Martella et al., 2005) has been suggested to be important for its AED activity in both veratridine-induced seizures (Otoom and Hasan, 2004) and amygdala-kindled rats (Borowicz and Czuczwar, 2003). Although the mechanisms of action for propofol remain unclear, it continues to be an effective alternative to barbiturates and benzodiazepines in the treatment of seizures without affecting normal neuronal activity (Hille, 1977; Rogawski and Loscher, 2004).

Propofol, HS245, and HS357 incorporate a potent and state-dependent sodium channel blocker (Lenkowski et al., 2004). In a previous study, we have also shown that the replacement of one phenyl ring in the structure of phenytoin with a seven-carbon alkyl chain resulted in important for sodium channel inhibition (Brown et al., 1999; Duch, 1999), to activate GABA currents in hippocampal neurons and APs evoked in CA1 neurons (Martella et al., 2005). However, its modulation of sodium currents (Martella et al., 2005) has been suggested to be important for its AED activity in both veratridine-induced seizures (Otoom and Hasan, 2004) and amygdala-kindled rats (Borowicz and Czuczwar, 2003). Although the mechanisms of action for propofol remain unclear, it continues to be an effective alternative to barbiturates and first line AEDs when treating refractory status epilepticus (Rossetti et al., 2004).

In this study, we have used propofol as a scaffold to design novel analogs. The first propofol analog, HS245, incorporates an α-hydroxyamide moiety we have shown previously to be important for sodium channel inhibition (Brown et al., 1999; Lenkowski et al., 2004). In a previous study, we have also shown that the replacement of one phenyl ring in the structure of phenytoin with a seven-carbon alkyl chain resulted in a potent and state-dependent sodium channel blocker (Lenkowski et al., 2004). To further determine the optimum distance between the phenyl and α-hydroxyamide moieties, we designed HS357, which incorporates a six-carbon alkyl linker (Fig. 1).

The effects of propofol, HS245, and HS357 were characterized on sodium channel currents recorded from cultured hippocampal neurons and APs evoked in CA1 neurons from rat hippocampal slices. In an effort to optimize in vitro conditions for burst firing and epileptiform events, we employed a hyperexcitation model obtained by perfusing brain slices with a zero Mg$^{2+}$/7 mM K$^+$ artificial cerebrospinal fluid (ACSF) solution that allows a higher magnitude depolarization and a stronger excitatory response (Mangan and Kapur, 2004; Arias and Bowby, 2005). In agreement with our observations in vitro, systemic administration of either propofol or HS357 protected mice from acute seizures observed in the 6-Hz (22-mA) partial seizure model; however, in contrast to propofol, the protection afforded by HS357 was not accompanied by motor impairment in the rotordot toxicity assay.

**Materials and Methods**

**Materials.** Propofol was obtained from Sigma-Aldrich (St. Louis, MO). HS245 and HS357 were synthesized as described in the supplemental data.

**Hippocampal Culture.** All experimental protocols were approved by the Institutional Animal Care and Use Committee affiliated with the University of Virginia and the University of Utah. All efforts were made to minimize animal stress and discomfort. The preparation of hippocampal cultures has been described previously (Mangan and Kapur, 2004). Briefly, hippocampi were dissected from 18-day-old rat embryos, dissociated by trypsin, and triturated with a Pasteur pipette. The neurons were plated on coverslips coated with poly-L-lysine in minimal essential medium with 10% horse serum at an approximate density of 25,000/cm$^2$. Once the neurons had attached to the substrate, they were transferred to a dish containing a glial monolayer and maintained for up to 4 weeks in serum-free minimal essential medium with N2 supplement. Voltage-clamp recordings were made from 1- to 2-week-old cultured hippocampal neurons.

**Brain Slice Preparation.** Transverse hippocampal slices (250–300 μm) were prepared from Sprague-Dawley rats (150–200 g). Animals were euthanized with halothane and decapitated, and brains were rapidly removed and placed in chilled (4°C) ACSF containing 125 mM NaCl, 2.5 mM KCl, 1.25 mM NaH$_2$PO$_4$, 2 mM CaCl$_2$, 1 mM MgCl$_2$, 0.5 mM l-aspartic acid, 10 mM glucose, 25 mM NaHCO$_3$, and 2 mM pyruvate (oxygenated with 95% O$_2$ and 5% CO$_2$). Slices were prepared using a Vibratome (Vibratome 1000 Plus, St. Louis, MO) and transferred to a chamber containing oxygenated ACSF, incubated at 37°C for 20 to 35 min, and then stored at room temperature. For recording, slices were held in a small chamber perfused with heated (32°C) oxygenated ACSF at 2 ml/min. CA1 hippocampal neurons were visually identified using a Zeiss Axioscope microscope (Zeiss, Oberkochen, Germany).

**Electrophysiology.** Sodium currents were recorded from cultured hippocampal neurons using the whole-cell configuration of the patch clamp recording technique with an Axopatch 200B amplifier (Axon Instruments, Foster City, CA). All voltage protocols were applied using Clampfit software (version 9; Axon Instruments) and a Digidata 1322A (Axon Instruments). Currents were acquired at 33 kHz and low-pass filtered at 2 kHz. Borosilicate glass pipettes were pulled using a Brown-Flaming puller (model P-87; Sutter Instruments Co., Novato, CA) and heat polished to produce electrode re-
sistances of 1.5 to 2.0 MΩ when filled with pipette solution containing 140 mM CsF, 2 mM MgCl₂, 1 mM EGTA, 10 mM HEPES, 4 mM Na₂ATP, and 0.3 mM NaGTP, pH adjusted to 7.3 with CsOH. Cultured neurons were perfused with solution containing 30 mM NaCl, 110 mM choline chloride, 3 mM KCl, 1 mM CaCl₂, 0.1 mM CdCl₂, 2 mM MgCl₂, 10 mM HEPES, and 30 mM TEA-Cl, pH adjusted to 7.3 with CsOH. Calcium and potassium currents were blocked by cadmium and TEA-Cl, respectively. On establishing the whole-cell configuration, neurons were held at −90 mV for 5 min to permit time for the equilibration of gating shifts. Currents were elicited from a holding potential of −90 mV by a step to −10 mV for 20 ms. Capacitive and leak currents were corrected for using standard P/4 protocols except during steady-state inactivation and use-dependent block protocols. All voltage clamp experiments were performed at room temperature (20–22°C). Current-clamp recordings were performed at 32°C in an ACSF extracellular solution described previously and an intracellular solution containing 120 mM potassium gluconate, 10 mM NaCl, 2 mM MgCl₂, 0.5 mM K₂EGTA, 10 mM HEPES, 4 mM NaATP, and 0.3 mM NaGTP, pH adjusted to 7.2 with KOH.

To induce spontaneous firing in hippocampal CA1 pyramidal neurons, slices were perfused (20 min) with a nominally zero Mg²⁺/Ca²⁺ ACSF solution containing 125 mM NaCl, 7 mM KCl, 1.25 mM NaH₂PO₄, 2 mM CaCl₂, 25 mM NaHCO₃, and 10 mM glucose (oxygenated with 95% O₂ and 5% CO₂), and the same intracellular solution was used for AP current-clamp recordings with the removal of MgCl₂. Compounds were prepared as 100 mM stock solutions in dimethylsulfoxide (DMSO) and diluted to desired concentrations in the respective extracellular solution. The total concentration of DMSO was maintained at less than 0.2% of the total volume.

### Data Analysis

IC₅₀ values were obtained by least-squares fitting of data to the Hill equation:

\[ I/I_{control} = 1/(1 + (C/IC_{50})^n) \]

where C is the concentration, IC₅₀ is the concentration that blocks 50% of the current, I is the current in the presence of the drug, I_control is the current in the absence of drug, and n is the Hill slope. Steady-state inactivation data were fitted to a Boltzmann equation of the form:

\[ I/I_{max} = 1/[1 + \exp(-(V - V_{1/2})/k)] \]

where \( I/I_{max} \) is the normalized current, \( I_{max} \) is the maximum current, \( V_{1/2} \) is the voltage of half-maximal inactivation, and \( k \) is the slope factor. The difference between the \( V_{1/2} \) value in the presence and absence of compound is shown as \( \Delta V_{1/2} \) (millivolts).

The affinities for the inactivated states of the channel were calculated using the steady-state inactivation curves in the presence of various concentrations of propofol (Bean et al., 1983; Kuo and Bean, 1994), according to the following equation:

\[ \Delta V_{1/2} = k \log[1 + (D/K_c)]/[1 + (D/K_i)] \]

where \( K_i \) is the binding affinity for the inactivated state, \( K_c \) is the binding affinity for the resting state (calculated from dose-response curves at −90 mV), \( D \) is the drug concentration, \( k \) is the slope of the steady-state inactivation curve, and \( \Delta V_{1/2} \) is the shift of the steady-state inactivation curve in the presence of drug compared with control.

Time constants for recovery from inactivation were obtained using a double exponential function:

\[ Y = A_1(1 - \exp(-t/\tau_1)) + A_2(1 - \exp(-t/\tau_2)) \]

where \( A_1 \) and \( A_2 \) are the amplitudes of the fast and slow exponentials, \( t \) is the time, and \( \tau_1 \) and \( \tau_2 \) are the fast and slow time constants. The percentage of the current represented by the fast time constant was calculated from the equation:

\[ A_1/(A_1 + A_2) \times 100\% \]

### Results

**Propofol and Analogs Block Sodium Currents in Hippocampal Neurons.** The chemical structures of propofol, HS245, and HS357 are shown in Fig. 1. We have previously shown that the replacement of the methyl group in themisone, an anticonvulsant used in the 1940s, with a trifluoro group yielded a compound with potent anticonvulsant activity in the maximal electric shock animal model of epilepsy (Choudhury-Mukherjee et al., 2003) (Fig. 1). In this study, we have continued to investigate the importance of both the trifluoro and the α-hydroxyamide groups of this themisone analog. Although HS245 explores the functional consequences of overlapping the phenyl rings of propofol with our themisone analog, HS357 explores the effects of separating the phenyl and the trifluoro/α-hydroxyamide portions of HS245 with a six-carbon alkyl linker (Fig. 1). Previous comparative molecular field analysis modeling studies have suggested that compounds with longer alkyl chains have an increased affinity for the inactivated state of the cardiac sodium channel (Lenkowski et al., 2004). Interestingly, the structural changes made to the propofol scaffold resulted in...
different lipophilicity values (log Ps) for propofol, HS245, and HS357 (3.63, 3.43, and 5.74, respectively).

**Propofol and Derivatives Affinities for the Inactivated State.** To determine the affinity for the resting state of the sodium channel, concentration-dependent curves were generated at a negative holding membrane potential of −90 mV (Fig. 2). When data were fit to the Hill equation, the IC50 at −90 mV (K9) values for propofol, HS245, and HS357 were 17.7, 100, and 24 μM with corresponding Hill slopes of 0.98, 1.84, and 1.50, respectively (Fig. 2A). Interestingly, both HS245 and HS357 had Hill slopes greater than 1, suggesting that the compounds could be interacting with more than one binding site. Example current traces are shown in Fig. 2B.

Propofol has been suggested previously to have a greater affinity for the inactivated state of the sodium channel (Rehberg and Duch, 1999). To test whether HS245 and HS357 also demonstrated a similar affinity, a two-pulse steady-state inactivation protocol with a 1-s prepulse was used (Fig. 3, A–C). Under drug-free conditions, the voltage of half-maximal inactivation (V1/2) was −56.4 ± 1.1 mV with a slope value (k) of 5.6 ± 0.2 mV (n = 28). In a similar manner to propofol, HS245 caused a concentration-dependent hyperpolarizing shift in V1/2. HS357 at the same concentrations caused a much greater shift in the V1/2 (Table 1). Slope factors (k) remained unchanged from those recorded in the absence of drug.

The affinity for the inactivated state of the channel for each compound was calculated from these concentration-dependent shifts in steady-state inactivation and tonic block data using the equation described previously in the data analysis section (Fig. 3D; Table 1). HS357 demonstrated a greater binding affinity for the inactivated state (K9 = 0.2 μM) compared with propofol (K9 = 0.7 μM), whereas HS245 had a lower binding affinity (K9 = 1.2 μM). Comparing the binding affinity with the resting state versus the inactivated state (K9/Ki) both HS245 and HS357 exhibited approximately a 4- to 5-fold greater K9/Ki ratio than their parent compound, propofol (Table 1).

**Propofol and Analogs Exhibit Use-Dependent Block.** Use-dependent blocking characteristics are thought to be important since they allow further block of sodium channels during sustained high-frequency depolarizations known to occur during seizure activity. To this end, use-dependent block of propofol and our compounds were examined using 10-Hz trains of depolarizing pulses to −10 mV from a holding potential of −90 mV (Fig. 4). Peak current amplitude was normalized to the first pulse in each experiment. Under control conditions, accumulation of inactivated channels resulted in a reduction in peak current amplitude by 30.4 ± 4.6% (n = 16). Propofol and HS357 were both tested at 30 μM, a concentration close to their IC50 values. At these concentrations, propofol and HS357 further reduced the current amplitude by 60.8 ± 3.2% (n = 5) and 79.5 ± 6.6% (n = 6), respectively (p < 0.01) after 6 s. Interestingly, when tested at a concentration lower than its IC50 (30 μM), HS245 exhibited significant (p < 0.01) use-dependent block, reducing the current amplitude to 50.7 ± 8.8% (n = 5). To assess the rate of development of use-dependent block, data were fitted with a single exponential function. Time constants for propofol, HS245, and HS357 were 2 ± 0.2, 2.9 ± 0.7, and 1.6 ± 0.1 s, respectively.

**Delay of Recovery from Inactivation.** Use-dependent block characteristics can arise from not only affinity for inactivated channels but also from a delay in recovery from inactivation kinetics. Therefore, we determined the effects of propofol, HS245, and HS357 on this parameter. Recovery from inactivation was assessed using a two-pulse protocol (Fig. 5). From a holding potential of −90 mV, a 1-s test pulse to 0 mV was applied, followed by a recovery step to −90 mV ranging from 1 ms to 100 s; currents were subsequently elicited by a second test pulse to −10 mV to assess recovery. In these experiments, compounds were assessed at a concentration close to their IC50 values (i.e., 30 μM for propofol and HS357 and 100 μM for HS245). Data were normalized to the current amplitude during the first test pulse and fitted using a double exponential function. Table 2 summarizes the recovery parameters for propofol and its analogs. Under control conditions, recovery from inactivation was best fit by a double exponential function representing the recovery of both fast and slow inactivated channels (Chen et al., 2006). In the presence of all test compounds, both fast and slow time constants were increased indicating a slowing of recovery kinetics. This was coupled with a significant decrease in the proportion of channels recovering with a fast time constant. The greatest modulation of recovery kinetics was observed in the presence of HS357.

**Propofol and HS357 Modulate Membrane Excitability and Epileptiform Activity.** In comparison with HS245, the actions of HS357 on sodium channel gating kinetics were more pronounced. In view of this, HS357 was selected to determine its effects on membrane excitability. The effects of propofol and HS357 on AP discharge and key parameters of
TABLE 1

<table>
<thead>
<tr>
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<th>3 μM</th>
<th>10 μM</th>
<th>30 μM</th>
<th>100 μM</th>
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<tr>
<td>ΔV_{1/2}</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Propofol</td>
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<td>-15.5 ± 1.4</td>
<td>N.D.</td>
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<tr>
<td>HS245</td>
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<td>-11.6 ± 1.6</td>
<td>-16.9 ± 3.6</td>
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<td>HS357</td>
<td>-14.4 ± 1.5*</td>
<td>-18.8 ± 1.5*</td>
<td>-23.2 ± 1.7*</td>
<td>N.D.</td>
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</tbody>
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* N.D., not determined.

*p < 0.01 vs. propofol with same concentration by one-way ANOVA (n = 4–5).

Fig. 3. Effects of propofol and analogs on steady-state inactivation curves in cultured hippocampal neurons. A to C, from a holding potential of −90 mV, prepulse potentials ranging from −105 to −20 mV were applied for 1 s followed by a depolarization step to −10 mV for 20 ms to elicit a current. Currents were normalized to the peak current elicited from the −105-mV test potential within each experiment. Smooth lines correspond to the average of the least-squares fits when data were fitted by the Boltzmann equation as described in the data analysis section. Propofol (10 μM), V_{1/2} = −68.3 ± 3.4 mV, k = 5.3 ± 0.3 mV, n = 4; propofol (30 μM), V_{1/2} = −70.8 ± 1.5 mV, k = 5.2 ± 0.3 mV, n = 4; HS245 (10 μM), V_{1/2} = −74.5 ± 1.8 mV, k = 5.1 ± 0.2 mV, n = 5; HS245 (30 μM), V_{1/2} = −81.7 ± 0.9 mV, k = 5.3 ± 0.3 mV, n = 4; HS357 (3 μM), V_{1/2} = −69.1 ± 2.7 mV, k = 5.4 ± 0.1 mV, n = 7; HS357 (30 μM), V_{1/2} = −74.9 ± 2.0 mV, k = 5.8 ± 0.3 mV, n = 5. Data points represent the mean ± S.E.M. D, smooth lines correspond to the average of the least-squares fits when data were fitted by the equation ΔV_{1/2} = k log(1 + (D/K)_i)/(1 + (D/K)_r) to calculate the affinity for the inactivated state (K_i). Data points represent the mean ± S.E.M (n = 4–7).

Effects of propofol and novel analogs on steady-state inactivation parameters

<table>
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<th>K_r</th>
<th>K_i</th>
<th>K_r/K_i</th>
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<tr>
<td>Propofol</td>
<td>-7.9 ± 1.0</td>
<td>17.7</td>
<td>0.7</td>
<td>23</td>
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<tr>
<td>HS245</td>
<td>-4.3 ± 2.2</td>
<td>100.0</td>
<td>1.2</td>
<td>83</td>
</tr>
<tr>
<td>HS357</td>
<td>-14.4 ± 1.5*</td>
<td>24.0</td>
<td>0.2</td>
<td>109</td>
</tr>
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</table>

The effects of propofol and HS357 on AP discharges in CA1 neurons in hippocampal slices. Typical resting membrane potential values for CA1 neurons under these recording conditions were −64.3 ± 2.4 mV (n = 11) and remained unaltered in the presence of both propofol and HS357. The effects of propofol and HS357 on APs elicited after a 300-ms current injection of 0.14 nA are shown in Fig. 6. Both propofol and HS357 caused a modest reduction in the number of APs evoked. At a concentration of 30 μM, APs were reduced from 6.8 ± 1.2 to 4.3 ± 0.9 (n = 4, p < 0.05) for propofol and from 6.9 ± 1.6 to 4.9 ± 1.6 (n = 7, p < 0.05) for HS357. These effects remained unchanged in the presence of picrotoxin (100 μM), a selective GABA_A antagonist. Under these conditions, HS357 (30 μM) reduced the number of APs from 6.7 ± 0.4 in control to 5.0 ± 0.72 (p < 0.05, n = 3) in the presence of drug. Neither propofol nor HS357 altered input resistance, AP amplitude, AP duration, or afterhyperpolarization amplitude. In contrast to propofol, HS357 increased the rheobase by 20 pA (p < 0.05, n = 7, data not shown). All effects were fully reversible upon washout.

To test the effects of propofol and HS357 on sustained spontaneous ictal-like AP discharges, CA1 pyramidal neurons in hippocampal slices were perfused with ACSF containing zero Mg<sup>2+</sup>/7 mM K<sup>+</sup>. The resulting enhanced neuronal excitability is thought to be comparable with epileptiform activity and is partially attributed to increased NMDA receptor activity as a result of reduced magnesium block (Mangan and Kapur, 2004). The perfusion of hippocampal slices (n = 9) with our modified ACSF solution (zero Mg<sup>2+</sup>/7 mM K<sup>+</sup>) resulted in sustained spontaneous discharges in CA1 pyramidal neurons (Fig. 7). The number of APs spontaneously generated during a 100-s period before perfusion of the test compound was considered as control and was compared with the number of APs elicited in the presence of test compounds and after

the AP were determined. Under current-clamp conditions, depolarizing current injections (0.02–0.16 nA, 300 ms) were used to elicit AP discharges in CA1 neurons in hippocampal slices. Typical resting membrane potential values for CA1 neurons under these recording conditions were −64.3 ± 2.4 mV (n = 11) and remained unaltered in the presence of both propofol and HS357. The effects of propofol and HS357 on APs elicited after a 300-ms current injection of 0.14 nA are shown in Fig. 6. Both propofol and HS357 caused a modest reduction in the number of APs evoked. At a concentration of 30 μM, APs were reduced from 6.8 ± 1.2 to 4.3 ± 0.9 (n = 4, p < 0.05) for propofol and from 6.9 ± 1.6 to 4.9 ± 1.6 (n = 7, p < 0.05) for HS357. These effects remained unchanged in the presence of picrotoxin (100 μM), a selective GABA_A antagonist. Under these conditions, HS357 (30 μM) reduced the number of APs from 6.7 ± 0.4 in control to 5.0 ± 0.72 (p < 0.05, n = 3) in the presence of drug. Neither propofol nor HS357 altered input resistance, AP amplitude, AP duration, or afterhyperpolarization amplitude. In contrast to propofol, HS357 increased the rheobase by 20 pA (p < 0.05, n = 7, data not shown). All effects were fully reversible upon washout.

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washout. Under control conditions, the average number of ictal discharges was 42.2 ± 6.5 (n = 9) and was reduced to 13.2 ± 2.7 in the presence of propofol (30 μM, n = 5, p < 0.01). After a 20-min period, only partial washout was observed for propofol (24.5 ± 5.0; Fig. 7A). In comparison, HS357 (30 μM, n = 4, p < 0.01) caused a further reduction in the number of epileptiform events, reducing it to 8.8 ± 2.0, and was completely reversible after a 20-min washout (40.0 ± 15.6). Once again, the effects of HS357 were unaffected by the presence of picrotoxin (100 μM). Specifically, the number of APs counted in a 100-s interval before drug application was 118 ± 40 and was reduced to 19 ± 11 in the presence of both HS357 (30 μM) and picrotoxin (100 μM; p < 0.05, n = 3). Furthermore, this effect, a 84.5 ± 5.9% reduction in the number of AP discharges in the presence of picrotoxin and HS357, was not significantly different (p = 0.79) from those observed in the presence of only HS357 (82.1 ± 8.0% reduction).

Anticonvulsant Activity and Toxicity of Propofol and HS357. To determine whether the modulation of sodium channel gating and decreased neuronal excitability observed in vitro would translate into anticonvulsant activity in vivo, test compounds were administered systemically to male CF-1 mice and tested in the 6-Hz (22-mA stimulation) partial psychomotor seizure model. Behavioral signs of toxicity were assessed using the mouse rotorod assay (Table 3). TPEs of 1.0 h for HS357 and approximately 5 min for propofol were determined after i.p. administration of the compounds. At their respective TPEs, both propofol and HS357 prevented partial seizure activity in the 6-Hz test. The ED50 observed after i.p. administration of propofol (15.8 mg/kg) was 2.8-fold lower than that observed for HS357 (56.3 mg/kg). However, the protection afforded by propofol was associated with significant sedation and motor impairment, which resulted in a TD50 of 18.0 mg/kg, consistent with propofol’s anesthetic properties. In contrast, HS357 was observed to be profoundly less toxic, as indicated by its 9-fold higher TD50 (155.7 mg/kg) than propofol. The observed ED50 and TD50 values for propofol and HS357 resulted in estimated PIs of 1.1 and 2.7, respectively. Taken together, these results demonstrate that HS357 not only exhibits anticonvulsant activity in the 6-Hz (22 mA) psychomotor seizure model but also possesses fewer toxic side effects than propofol.
Propofol at subanesthetic concentrations exhibits anticonvulsant properties in refractory status epilepticus patients (Brown and Levin, 1998; Prasad et al., 2001; Rossetti et al., 2004). However, several studies have cautioned against the use of propofol as an anticonvulsant because of serious side effects (Claassen et al., 2002; Marik, 2004). Although propofol is known to enhance GABA currents and inhibit Ca\(^{2+}\) channels, its modulation of neuronal sodium channels is thought to be a major determinant for its AED activity (Orser et al., 1994; Rehberg and Duch, 1999; Martella et al., 2005).

In this study, we have synthesized two novel analogs of propofol and characterized their effects on sodium channel gating. One of the propofol derivatives, HS357, inhibited spontaneously generated APs and protected against seizures generated in 6-Hz (22 mA) psychomotor model with less behavioral toxicity than propofol.

### Biophysical Properties of Propofol Analogs Parallel Physicochemical and Structural Properties.

Propofol caused tonic inhibition of sodium channel currents recorded from cultured hippocampal neurons with an IC\(_{50}\) value of 17 \(\mu\)M, consistent with values reported for Na\(_{1.2}\) \(\alpha\)-subunits expressed in Chinese hamster ovary cells (Rehberg and Duch, 1999). In contrast, addition of an \(\alpha\)-hydroxyamide to the phenyl ring of propofol resulted in HS245 and a 5-fold lower affinity for the resting state but only a 1.6-fold difference in affinity for the inactivated state. Interestingly, HS357, which incorporates an alkyl linker between the

### TABLE 2

The effects of novel propofol analogs on recovery from inactivation parameters

<table>
<thead>
<tr>
<th>Condition</th>
<th>(\tau_1) (\pm) SD (ms)</th>
<th>(A_1) (\pm) SD</th>
<th>(\tau_2) (\pm) SD (ms)</th>
<th>(A_2) (\pm) SD</th>
<th>Fast (\pm) SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>7.7 (\pm) 1.7</td>
<td>0.52 (\pm) 0.08</td>
<td>1830 (\pm) 620</td>
<td>0.51 (\pm) 0.07</td>
<td>52.5 (\pm) 7.4</td>
</tr>
<tr>
<td>Propofol (30 (\mu)M)</td>
<td>71.0 (\pm) 14.1**</td>
<td>0.28 (\pm) 0.06</td>
<td>5710 (\pm) 780**</td>
<td>0.73 (\pm) 0.06</td>
<td>27.8 (\pm) 6.1*</td>
</tr>
<tr>
<td>Control</td>
<td>6.8 (\pm) 2.5</td>
<td>0.69 (\pm) 0.14</td>
<td>1300 (\pm) 400</td>
<td>0.45 (\pm) 0.06</td>
<td>59.3 (\pm) 7.9</td>
</tr>
<tr>
<td>HS245 (100 (\mu)M)</td>
<td>91.5 (\pm) 8.4*</td>
<td>0.29 (\pm) 0.05</td>
<td>11600 (\pm) 2400**</td>
<td>0.81 (\pm) 0.05</td>
<td>19.7 (\pm) 4.8**</td>
</tr>
<tr>
<td>Control</td>
<td>5.6 (\pm) 1.0</td>
<td>0.59 (\pm) 0.07</td>
<td>1900 (\pm) 360</td>
<td>0.53 (\pm) 0.05</td>
<td>58.0 (\pm) 11.8</td>
</tr>
<tr>
<td>HS357 (30 (\mu)M)</td>
<td>43.1 (\pm) 15.2**</td>
<td>0.15 (\pm) 0.05</td>
<td>15700 (\pm) 1100**</td>
<td>0.85 (\pm) 0.05</td>
<td>15.2 (\pm) 4.7**</td>
</tr>
</tbody>
</table>

\*\(p < 0.05\) vs. respective control by one-way ANOVA (\(n = 4–5\)).
**\(p < 0.01\) vs. respective control by one-way ANOVA (\(n = 4–5\)).
amide and phenyl groups, exhibited a comparable resting state inhibition with that of propofol but a 3.6-fold greater affinity for the inactivated state compared with propofol. These distinct biophysical properties observed for propofol and its derivatives may parallel differences in their physicochemical and structural properties. First, it is possible that direct addition of the α-hydroxyamide moiety to the phenyl ring of propofol destabilizes the molecular interactions of HS245 with the closed state of the channel, whereas it has little effect on interactions formed with the inactivated state (Table 1). The addition of the α-hydroxyamide moiety to HS245 would increase the steric bulk around the phenyl ring, allowing a less favored interaction with the resting state binding site. Conversely, addition of the aliphatic chain in HS357 affords a greater distance between the bulky binding site. Conversely, addition of the aliphatic chain in HS357 would increase the steric bulk around the phenyl ring of propofol and become more accessible to the resting state. HS357's more pronounced inhibition of epileptic events may be explained by their greater affinities for the inactivated state. HS357's more pronounced inhibition of epileptiform events than current-evoked APs. These results are consistent with previous studies showing selective inhibition by propofol of low Mg$^{2+}$-induced epileptiform activity over current-evoked APs in cortical neurons (Martella et al., 2005). In these studies, bicuculline abolished the effects of propofol on current-evoked APs but not on low Mg$^{2+}$-induced APs. In contrast, HS357's effects on both current-evoked APs and low Mg$^{2+}$-induced APs were unchanged in the presence of picrotoxin, a selective GABA$_A$ antagonist, suggesting that HS357's actions were not mediated by the potentiation of GABA currents. However, effects on other ion channel targets cannot be ruled out.

During spontaneous epileptic events, sodium channels rapidly cycle through the closed, activated, and inactivated states. According to the modulated receptor hypothesis (Hille, 1977), sodium channels accumulate in high-affinity drug binding conformations (i.e., open and/or inactivated states) and therefore the inhibitory effects of propofol and HS357 on epileptiform events may be explained by their greater affinities for the inactivated state. HS357's more pronounced inhibition of epileptic events compared to propofol could be attributed to its 4-fold greater $K_r/K_i$ ratio than propofol, resulting in greater use-dependent block and further delay of recovery from inactivation. These mechanisms would reduce sodium channel availability during high-frequency repetitive firing (Ragsdale and Avoli, 1998; Rogawski and Loscher, 2004).

### In Vivo Studies and Therapeutic Implication for a Novel Propofol Analog

Our behavioral studies in the 6-Hz partial seizure model support our hypothesis that structural changes in the propofol scaffold can result in novel compounds with anticonvulsant activity. At efficacious doses (30 mg/kg), propofol caused marked sedation and ataxia, whereas HS357 (100 mg/kg) displayed little or no side effects at higher doses. The approximate 2-fold difference in PI values for propofol and HS357 may again be attributed to HS357's far greater selectivity for the inactivated over resting state of the sodium channel (i.e., $K_r/K_i$ ratios). In other words, increased $K_r/K_i$ ratios for sodium channel blockers may indicate greater in vivo efficacy with fewer side effects.

### Table 3

Anticonvulsant effects of propofol and HS357 tested using the 6-Hz (22-mA) psychomotor seizure model and rotorod toxicity

<table>
<thead>
<tr>
<th>Compound</th>
<th>ED$_{50}$</th>
<th>TD$_{50}$</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propofol</td>
<td>15.8 (6.09–92.8)</td>
<td>18.0 (13.0–24.4)</td>
<td>1.1</td>
</tr>
<tr>
<td>HS357</td>
<td>56.3 (21.6–101.7)</td>
<td>155.7 (88.7–8295.1)</td>
<td>~2.8</td>
</tr>
</tbody>
</table>

* Poor suspension obtained at concentrations > 150 mg/kg precluded accurate determination of the PI.
by favoring a block of sustained high-frequency firing, which is known to occur during epileptic activity, without interfering with normal neuronal firing.

The greater protective index of HS357 is a desirable characteristic for a potential AED and warranted in the therapeutic treatment of seizure suppression (Brodie, 2001). Equally important to improved tolerability is the identification of new AEDs with potential efficacy in therapy resistance patients (Brodie, 2001). Previous studies have implicated the use of the 6-Hz model (22–44 mA) for identifying potentially useful AEDs and differentiating those that may be effective for patients with therapy-resistant epilepsies (Barton et al., 2001). For example, levetiracetam, an AED used to treat refractory human partial seizures, was effective in the 6-Hz model (22, 32, and 44 mA) but inactive in the maximal electroshock and s.c. metrazole seizure models (Barton et al., 2001). Other anticonvulsant agents, including phenytoin, lamotrigine, and ethosuximide, were effective at blocking seizures in the 6-Hz model at 22 mA but were unable to maintain this protection at 32 mA (phenytoin, lamotrigine) or at 44 mA (ethosuximide). Here, we show that HS357 is not only effective in the 6-Hz model at 22 mA but also better tolerated than its parent compound, propofol. Given the activity identified at the 22-mA current intensity, it will be important to determine the potential utility of HS357 and/or propofol in the 6-Hz partial seizure model at higher current intensities to determine whether these compounds would offer any potential benefit for refractory seizure activity.

In summary, clinical and experimental results have established sodium channel blockers as effective treatments of epilepsy. Here, we describe the effects of propofol and two derivatives, HS245 and HS357, on sodium currents recorded from hippocampal neurons. HS357 demonstrated a greater affinity for the inactivated state of the sodium channel and protected mice against seizures in the 6-Hz seizure model. Furthermore, HS357 displayed a greater safety margin than propofol with regards to impairment of motor coordination, suggesting that propofol analogs could be an important structural class in the development of new AEDs.

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References


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