Volatile Anesthetic Effects on Glutamate versus GABA Release from Isolated Rat Cortical Nerve Terminals: 4-Aminopyridine-Evoked Release

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ABSTRACT

Inhibition of glutamatergic excitatory neurotransmission and potentiation of GABA-mediated inhibitory transmission are possible mechanisms involved in general anesthesia. We compared the effects of three volatile anesthetics (isoflurane, enflurane, or halothane) on 4-aminopyridine (4AP)-evoked release of glutamate and GABA from isolated rat cerebrocortical nerve terminals (synaptosomes). Synaptosomes were prelabeled with [3H]glutamate and [14C]GABA, and release was evoked by superfusion with pulses of 1 mM 4AP in the absence or presence of 1.9 mM free Ca2+. All three volatile anesthetics inhibited Ca2+-dependent glutamate and GABA release; IC50 values for glutamate were comparable to clinical concentrations (1–2.2 × MAC), whereas IC50 values for GABA release exceeded clinical concentrations (>2.2 × MAC). All three volatile anesthetics inhibited both Ca2+-independent and Ca2+-dependent 4AP-evoked glutamate release equipotently, whereas inhibition of Ca2+-dependent 4AP-evoked GABA release was less potent than inhibition of Ca2+-independent GABA release. Inhibition of Ca2+-independent 4AP-evoked glutamate release was more potent than that of GABA release for isoflurane and enflurane but equipotent for halothane. Tetrodotoxin inhibited both Ca2+-independent and Ca2+-dependent 4AP-evoked glutamate and GABA release equipotently, consistent with Na+ channel involvement. In contrast to tetrodotoxin, volatile anesthetics exhibited selective effects on 4AP-evoked glutamate versus GABA release, consistent with distinct mechanisms of action. Preferential inhibition of Ca2+-dependent 4AP-evoked glutamate release versus GABA release supports the hypothesis that reduced excitatory neurotransmission relative to inhibitory neurotransmission contributes to volatile anesthetic actions.

Depression of neuronal activity by general anesthetics appears to involve inhibition of excitatory glutamatergic neurotransmission and enhancement of inhibitory GABAAergic neurotransmission (Hemmings et al., 2005a). Positive modulation of postsynaptic GABA A receptor function at GABAAergic synapses is probably an important component of the depressant effects of volatile anesthetics (Jones et al., 1992; Franks and Lieb, 1994; Maclver, 1997). However, spinal GABA A receptor potentiation does not explain the immobilizing action characteristic of volatile anesthetics (Zhang et al., 2004). Accumulating evidence indicates that volatile anesthetics affect multiple synaptic targets, both presynaptically and postsynaptically, that interact to produce their clinical effects (Maclver, 1997; Stucke et al., 2002; Hemmings et al., 2005a).

Action potential-evoked neurotransmitter release involves nerve-terminal depolarization that triggers Ca2+ entry through voltage-gated Ca2+ channels coupled to synaptic vesicle exocytosis (Südhof, 2004). Basal neurotransmitter release includes spontaneous vesicular fusion and nonvesicular release via reverse transporter operation independent of Ca2+ entry. These pathways of release are mechanistically distinct and are therefore differentially sensitive to presynaptic neuromodulators (Engelman and MacDermott, 2004). In the accompanying report (Westphalen and Hemmings, 2005), we show that volatile anesthetics produce significant transmitter-selective and agent-specific effects on basal glutamate and GABA release that results in a consistent net increase in inhibitory relative to excitatory basal transmitter release.

Neurotransmitter release from isolated nerve terminals can be evoked pharmacologically by 4AP, a K+ channel blocker that induces release by mimicking action potential-evoked depolarizations (Tibbs et al., 1989). Inhibition of 4AP-evoked glutamate release by volatile anesthetics seems to involve suppression of presynaptic voltage-gated Na+ channels coupled to transmitter release (Schlame and Hemmings, 1994; Franks and Lieb, 1994; MacIver, 1997). However, spinal depressant effects of volatile anesthetics (Jones et al., 1992; MacIver, 1997) are probably an important component of the enhancement of inhibitory neurotransmission and enhancement of inhibitory GABAergic neurotransmission (Hemmings et al., 2005a). Positive modulation of postsynaptic GABA A receptor function at GABAAergic synapses is probably an important component of the depressant effects of volatile anesthetics (Jones et al., 1992; Franks and Lieb, 1994; Maclver, 1997). However, spinal GABA A receptor potentiation does not explain the immobilizing action characteristic of volatile anesthetics (Zhang et al., 2004). Accumulating evidence indicates that volatile anesthetics affect multiple synaptic targets, both presynaptically and postsynaptically, that interact to produce their clinical effects (Maclver, 1997; Stucke et al., 2002; Hemmings et al., 2005a).

ABBREVIATIONS: 4AP, 4-aminopyridine; MAC, minimum alveolar concentration; FR, fractional release.
1995; Ratnakumari et al., 2000; Westphalen and Hemmings, 2003a). However, Na\(^+\) channel block does not affect spontaneous transmitter release (Engelman and MacDermott, 2004), and anesthetics modulate basal release independent of their Na\(^+\) channel antagonism. Here we compare the effects of three widely used volatile anesthetics, the ethers isoflurane and enflurane and the alkane halothane, and the selective voltage-gated Na\(^+\) channel blocker tetrodotoxin on 4AP-evoked release of glutamate and GABA while compensating for their agent-specific effects on basal release (Westphalen and Hemmings, 2005).

Materials and Methods

Materials. Sources of all compounds are listed in the accompanying article (Westphalen and Hemmings, 2005).

Evoked Glutamate and GABA Release ± Anesthetics. Experiments were done in accordance with the National Institutes of Health Guidelines for the Care and Use of Laboratory Animals as approved by the Weill Medical College of Cornell University Institutional Animal Care and Use Committee. Synaptosomes were prepared from rat cerebral cortex and prelabeled with \(^{\text{[3H]}}\)glutamate and \(^{\text{[14C]}}\)GABA, whereupon simultaneous \(^{\text{[3H]}}\)glutamate and \(^{\text{[14C]}}\)GABA release was evoked by pulses of 1 mM 4AP as described in the accompanying article (Westphalen and Hemmings, 2005).

Using \(^{\text{[3H]}}\)H\(_2\)O as a tracer, a 2-min pulse resulted in a peak of 70 ± 4% of the applied concentration to the perfusion chamber, suggesting a maximum concentration of 0.7 mM 4AP exposure to synaptosomes (data not shown). The accuracy of the dual radiolabel assay has been verified previously in detecting changes in the release of each amino acid independently of the other (Westphalen and Hemmings, 2003b).

Anesthetics at 0.1 to 8 × MAC (minimum alveolar concentration) were applied for 6 min (3 min before, during, and 1 min after stimulation with a 2-min pulse of 4AP) using a closed superfusion system (Westphalen and Hemmings, 2005). This procedure insures the exposure to anesthetic throughout the 4AP-evoked release pulse (Westphalen and Hemmings, 2003a). After each experiment, anesthetic solutions were sampled and quantified by gas chromatography as described previously (Westphalen and Hemmings, 2005). In separate experiments, anesthetics were continuously applied 12 min prior to stimulation by 4AP and remained present throughout the perfusion, with comparable effects on release.

Data Analysis. Release in each fraction was expressed as a fraction of synaptosomal content of labeled transmitter prior to each fraction collected (fractional release [FR]). The magnitude of the release pulse was determined by subtracting baseline release (average of basal release before and after pulse) from cumulative fractional release values for the release pulse (sum ΔFR; Garcia-Sanz et al., 2001). Sum ΔFR data for each experiment were normalized by the ratio of the individual assay control to the mean of all assay controls for release in the absence or presence of Ca\(^{2+}\) for each anesthetic used prior to curve fitting.

Concentration-effect data for anesthetic effects on basal \(^{\text{[3H]}}\)glutamate and \(^{\text{[14C]}}\)GABA release were taken from Westphalen and Hemmings (2005). The basal effect on sum ΔFR for each anesthetic concentration was determined from the fitted equation and was subtracted from the sum ΔFR values determined for 4AP-evoked release. Likewise, the derived Ca\(^{2+}\)-independent release values were subtracted from values obtained in the presence of Ca\(^{2+}\) at equivalent anesthetic concentrations to determine Ca\(^{2+}\)-dependent release. This subtraction method is standard procedure when baseline measurements of x-axis data cannot be accurately duplicated (Prism, version 4.0; GraphPad Software Inc., San Diego, CA).

Data for anesthetic (0.1–8 × MAC) and tetrodotoxin (0.3 nM-10 μM) inhibition of 4AP-evoked release (with basal effect subtracted) were fitted to concentration-effect curves by least-squares analysis to estimate \(I_{\text{max}}\) and IC\(_{50}\) with means ± S.E. (Prism, version 4.0). Each curve fit was concurrently tested for the bottom of the curve (\(I_{\text{max}}\)) differing significantly from 0. If the null hypothesis (\(I_{\text{max}} = 0\)) was not rejected, curve fit analyses were performed with \(I_{\text{max}}\) constrained to 0. Sum ΔFR values for all single concentration experimental groups followed Gaussian distributions, with some significantly differing in variance, as determined by a modification of the Kolmogorov and Smirnov test and Bartlett's test, respectively. Significant differences between mean sum ΔFR values and between concentration-effect curve parameters were determined by unpaired Student's t test with Welch correction for variances that were not assumed to be equal (Prism, version 4.0). Sum ΔFR values obtained for 4AP-evoked release in the presence of continuously applied anesthetics were compared with the corresponding values read from inhibition curves with the basal effect subtracted by paired Student's t test.

Results

4-Aminopyridine-Evoked Release. Stimulation of rat cerebrocortical synaptosomes with 1 mM 4AP in the presence of 1.9 mM free external Ca\(^{2+}\) evoked both \(^{\text{[3H]}}\)glutamate and \(^{\text{[14C]}}\)GABA release (Figs. 1–4). Total release (sum ΔFR) was greater for \(^{\text{[14C]}}\)GABA release compared with \(^{\text{[3H]}}\)glutamate, as reported previously (Westphalen and Hemmings, 2003a).

Isoflurane. Isoflurane inhibited glutamate and GABA release in a concentration-dependent manner (Fig. 1). Concentration-effect curves showed that isoflurane inhibited 4AP-evoked release of \(^{\text{[3H]}}\)glutamate (Fig. 1A) and \(^{\text{[14C]}}\)GABA (Fig. 1B), both in the absence and presence of Ca\(^{2+}\). At concentrations up to 1 mM isoflurane, maximal inhibition of \(^{\text{[3H]}}\)glutamate release was greater than maximal inhibition of \(^{\text{[14C]}}\)GABA release. However, at concentrations >1 mM isoflurane, sum ΔFR values increased from maximal inhibition. This augmentation of release paralleled the effects on basal release previously observed at high isoflurane concentrations (Westphalen and Hemmings, 2005), as evident in Fig. 1, A and B. Subtraction of the effects of isoflurane on basal release from 4AP-evoked release yielded data that fitted sigmoidal concentration-effect curves with 100% inhibition for both \(^{\text{[3H]}}\)glutamate release (\(I_{\text{max}} = 0, P = 0.84;\) Fig. 1C) and \(^{\text{[14C]}}\)GABA release (\(I_{\text{max}} = 0, P = 0.37;\) Fig. 1D) and were comparable to release evoked during continuously perfused anesthetic (see legend to Fig. 1). Isoflurane inhibited evoked \(^{\text{[3H]}}\)glutamate release with greater potency than \(^{\text{[14C]}}\)GABA release in the presence of Ca\(^{2+}\) (\(P = 0.0001;\) Table 1). This selective inhibition by isoflurane is not due to the lower fractional release of glutamate versus GABA evoked by 1 mM 4AP, as shown previously by matching fractional release by lowering 4AP concentration (Westphalen and Hemmings, 2003a). In the absence of Ca\(^{2+}\), isoflurane inhibited 4AP-evoked release of \(^{\text{[3H]}}\)glutamate with lower potency than \(^{\text{[14C]}}\)GABA release (\(P < 0.0001;\) Table 1), with efficacies of 100% for both (\(P_{\text{max}} = 0.67\) and \(P = 0.37,\) respectively). Isoflurane inhibited Ca\(^{2+}\)-dependent and Ca\(^{2+}\)-independent 4AP-evoked \(^{\text{[3H]}}\)glutamate release at clinically relevant concentrations (IC\(_{50}\) = 0.58 mM; 1.7 × MAC) with the same potency (\(P = 0.98\)) and both with greater potency (\(P < 0.0001\)) than Ca\(^{2+}\)-dependent 4AP-evoked \(^{\text{[14C]}}\)GABA release (IC\(_{50}\) = 1.06 mM; 3.0 × MAC; Table 1). Isoflurane inhibited Ca\(^{2+}\)-independent 4AP-evoked \(^{\text{[14C]}}\)GABA release with greater potency than Ca\(^{2+}\)-dependent release (\(P < 0.0001;\) Table 1).
Enflurane. Enflurane inhibited 4AP-evoked release of L-[3H]glutamate and [14C]GABA in a concentration-dependent manner (Fig. 2, A and B). Maximum inhibition of L-[3H]glutamate release was indeterminable from these data, which trended negative at concentrations >0.8 mM, apparently as a consequence of the inhibitory effect of enflurane on basal glutamate release (Westphalen and Hemmings, 2005). With basal release subtracted, enflurane inhibited both L-[3H]glutamate and [14C]GABA release by 100% \(I_{max} = 0\), \(P = 0.98\) and \(P = 0.25\), respectively; Fig. 2, C and D). The potency of enflurane for inhibition of 4AP-evoked L-[3H]glutamate release was greater than that for [14C]GABA release \((P < 0.0001; \text{Table 1})\). In the absence of Ca\(^{2+}\), enflurane completely inhibited 4AP-evoked release of L-[3H]glutamate and [14C]GABA \((I_{max} = 0, P = 0.57\) and \(P = 0.12\), respectively; \text{Table 1}; Fig. 2, C and D). Enflurane inhibited Ca\(^{2+}\)-independent [14C]GABA release with greater potency than Ca\(^{2+}\)-dependent release \((P < 0.0001; \text{Table 1})\). Enflurane inhibited Ca\(^{2+}\)-independent 4AP-evoked [14C]GABA release with greater potency than Ca\(^{2+}\)-dependent release \((P < 0.0001; \text{Table 1})\). Enflurane inhibited Ca\(^{2+}\)-independent 4AP-evoked [14C]GABA release with greater potency than Ca\(^{2+}\)-dependent release \((P < 0.0001; \text{Table 1})\).

Halothane. Halothane inhibited 4AP-evoked release of L-[3H]glutamate and [14C]GABA in a concentration-dependent manner (Fig. 3, A and B). With basal release subtracted, halothane inhibited both L-[3H]glutamate and [14C]GABA release by 100% \(I_{max} = 0\), \(P = 0.84\) and \(P = 0.78\), respectively; \text{Fig. 3, C and D}). Halothane inhibited 4AP-evoked L-[3H]glutamate release with greater potency than [14C]GABA release \((P < 0.001; \text{Table 1})\). In the absence of Ca\(^{2+}\), halothane inhibited 4AP-evoked release of L-[3H]glutamate and [14C]GABA with similar potencies \((P = 0.93)\) and 100% efficacy \((I_{max} = 0, P = 0.88\) and \(P = 0.08\), respectively; \text{Table 1}; Fig. 3, C and D). Halothane inhibited Ca\(^{2+}\)-dependent L-[3H]glutamate release at clinically relevant concentrations \((I_{50} = 0.56 \text{ mM}; 1.6 \times \text{MAC})\) with the same potency as Ca\(^{2+}\)-independent 4AP-evoked L-[3H]glutamate release \((P = 0.085; \text{Table 1})\). Halothane inhibited Ca\(^{2+}\)-dependent [14C]GABA release \((I_{50} = 0.76 \text{ mM}; 2.2 \times \text{MAC})\) with less potency than Ca\(^{2+}\)-independent release \((P = 0.008; \text{Table 1})\).

Tetrodotoxin. Tetrodotoxin inhibited 4AP-evoked release of L-[3H]glutamate and [14C]GABA in a concentration-depen-
dent manner (Fig. 4, A and B). With basal effects subtracted, tetrodotoxin showed incomplete efficacy for inhibition of both 4AP-evoked L-[3H]glutamate release (66% inhibition; \(I_{\text{max}} = 0, P = 0.0024\)) and [14C]GABA release (46% inhibition; \(I_{\text{max}} = 0, P = 0.0022\)) in the presence of Ca\(^{2+}\) (Fig. 4, C and D). Tetrodotoxin inhibited 4AP-evoked L-[3H]glutamate and [14C]GABA release with the same potency (\(P = 0.78\); Table 1). The effects of tetrodotoxin on Ca\(^{2+}\)-independent 4AP-evoked L-[3H]glutamate and [14C]GABA release were not statistically significant with basal effects subtracted (Fig. 4, C and D). Thus, curve parameters for Ca\(^{2+}\)-dependent inhibition of evoked release of glutamate and GABA were the same (Table 1). However, inhibition of Ca\(^{2+}\)-dependent glutamate release was complete (\(I_{\text{max}} = 0, P = 0.06\)) but was incomplete for inhibition of Ca\(^{2+}\)-dependent GABA release (\(I_{\text{max}} = 0, P = 0.026\)). This difference in maximal inhibition of Ca\(^{2+}\)-dependent release by tetrodotoxin between glutamate and GABA was also statistically significant by a comparative curve fit (\(P = 0.044\)).

**Tetrodotoxin-Insensitive 4-Aminopyridine-Evoked Release.** In the presence of Ca\(^{2+}\) and 1 \(\mu\)M tetrodotoxin (a concentration that maximally inhibited 4AP-evoked L-[3H]glutamate and [14C]GABA release; Fig. 4, C and D), the tetrodotoxin-insensitive 4AP-evoked [14C]GABA release was significantly inhibited by 0.7 mM isoflurane (\(P < 0.001\)), 1.8 mM enflurane (\(P < 0.001\)), or 0.7 mM halothane (\(P < 0.001\)) (Fig. 5). Inhibition of the residual tetrodotoxin-insensitive 4AP-evoked L-[3H]glutamate release was not significant for any anesthetic.

**Discussion**

Isoflurane, enflurane, and halothane all selectively inhibited Ca\(^{2+}\)-dependent 4AP-evoked glutamate release compared with GABA release. Taking into consideration anesthetic-specific effects on basal release (Westphalen and Hemmings, 2005), the volatile anesthetics inhibited glutamate release with greater potencies within a clinically relevant concentration range and with full efficacies. This refined analysis clarifies the finding of different efficacies when basal effects are not considered (Westphalen and Hemmings, 2003a). Because depolarization-evoked vesicular transmitter release is Ca\(^{2+}\)-dependent, these results support preferential inhibition of evoked vesicular glutamate release over GABA...
release by a variety of clinically used volatile anesthetics. The effects of volatile anesthetics on both basal and evoked release of the major excitatory and inhibitory transmitters may combine to depress overall central nervous system neuronal activity. The significant actions of volatile anesthetics on basal release highlight the need to consider these effects when analyzing drug effects on evoked release data.

Different volatile anesthetic potencies for inhibition of glutamate versus GABA release by volatile anesthetics suggest underlying physiological difference(s) between glutamatergic and GABAergic nerve terminals resulting in distinct transmitter-selective pharmacologies. Voltage-gated Na⁺ channels are important in the generation of neuronal action potentials that trigger exocytosis of synaptic vesicles (Tibbs et al., 1989; Südhof, 2004). Mammalian Na⁺ channels show selective densities within and between neurons (Goldin, 2001; Novakovic et al., 2001), can modulate transmitter release (Engelman and MacDermott, 2004), and are inhibited by volatile anesthetics (see below). Thus, inhibition by volatile anesthetics of evoked neurotransmitter release might occur via Na⁺ channel block. This hypothesis is supported by the present demonstration that 4AP-evoked release is also inhibited by the selective Na⁺ channel blocker tetrodotoxin. Moreover, volatile anesthetics inhibit 4AP-evoked (action potential-evoked) transmitter release with greater potency than release evoked by elevated K⁺ entry (Schnke and Hemmings, 1995; Ratnakumari et al., 2000; Westphalen and Hemmings, 2003a; Hemmings et al., 2005b), which implies an anesthetic target upstream of Ca²⁺ entry. Additional support for volatile anesthetic inhibition of mammalian neuronal Na⁺ channels includes anesthetic inhibition of synaptosomal influx of ²²Na⁺ and [³H]batrachotoxinin-A binding to nerve-terminal Na⁺ channels (Ratnakumari and Hemmings, 1998), inhibition of heterogeneously expressed brain Na⁺ channels (Rehberg et al., 1996; Shiraishi and Harris, 2004), and inhibition of Na⁺ currents in isolated rat dorsal root ganglion neurons (Ratnakumari et al., 2000) and isolated neurohypophysial nerve terminals (Ouyang et al., 2003; Ouyang and Hemmings, 2005).

Isoflurane, enfurane, and halothane completely inhibited Ca²⁺-dependent 4AP-evoked glutamate and GABA release with potencies comparable to inhibition of mammalian voltage-gated Na⁺ channels (Rehberg et al., 1996; Ouyang et al., 2003). In contrast, the selective Na⁺ channel blocker tetro-
dotoxin completely inhibited \( \text{Ca}^{2+} \)-dependent 4AP-evoked glutamate release but only partially inhibited GABA release. This is consistent with a previous study that showed tetrodotoxin-resistant \( \text{Ca}^{2+} \)-dependent 4AP-evoked inhibitory postsynaptic currents in rat hippocampus (Akaike, 2002). Preferential inhibition of autaptic excitatory postsynaptic currents versus inhibitory postsynaptic currents by \( \text{Na}^{+} \) channel blockers in hippocampal neuron microcultures (Prakriya and Mennerick, 2000) suggests fundamental differences in the distribution and/or function of \( \text{Na}^{+} \) channels between glutamate and GABA nerve terminals. The potency of tetrodotoxin in inhibiting both glutamate and GABA release corresponds to the tetrodotoxin-sensitive \( \text{Na}^{+} \) channel subtypes \( \text{NaV}1.1, 1.2, 1.3, 1.6, \) and/or 1.7 (Novakovic et al., 2001; Lai et al., 2004). Perhaps the tetrodotoxin-insensitive fraction of 4AP-evoked GABA release involves expression of tetrodotoxin-resistant \( \text{Na}^{+} \) channel subtypes (e.g., \( \text{NaV}1.8 \) and/or 1.9; Novakovic et al., 2001; Lai et al., 2004) in a subset

![Fig. 4. Tetrodotoxin effects on evoked release. Tetrodotoxin effects on L-[3H]glutamate (A) and [14C]GABA (B) evoked by 4AP from rat cortical synaptosomes were fitted to sigmoidal concentration-effect curves. Control data in the presence of \( \text{Ca}^{2+} \) (glutamate, \( n = 7 \); GABA, \( n = 7 \)) or absence of \( \text{Ca}^{2+} \) (glutamate, \( n = 6 \); GABA, \( n = 6 \)) are presented as mean \pm S.D. Basal effects (taken from Westphalen and Hemmings, 2005) were subtracted from evoked release data and the difference fitted to sigmoidal concentration-effect curves (C and D). Tetrodotoxin did not completely inhibit L-[3H]glutamate or GABA release in the presence of \( \text{Ca}^{2+} \), or significantly inhibit \( \text{Ca}^{2+} \)-independent L-[3H]glutamate or GABA release. Symbols in gray present sum FR data (mean \pm S.D.) for 2-min pulses of 1 mM 4AP in the presence of \( \text{Ca}^{2+} \) and 10 nM (\( n = 4 \)), 100 nM (\( n = 4 \)), or 1 \( \mu \text{M} \) (\( n = 6 \)) tetrodotoxin applied continuously, which do not differ from data obtained using the standard pulse application with basal effect subtracted (glutamate, \( P = 0.16 \); GABA, \( P = 0.10 \)). Release in the absence of anesthetic presents mean of all assay controls.

Table 1: Inhibition potencies of 4-aminopyridine-evoked L-[3H]glutamate and [14C]GABA release

Values were derived by fitting data to sigmoidal concentration effect-curves (see Materials and Methods). Statistical significance between glutamate and GABA (\( * \), \( P < 0.05 \); \( ** \), \( P < 0.01 \); \( *** \), \( P < 0.001 \)) and between \( -\text{Ca}^{2+} \) and \( \text{Ca}^{2+} \)-dependent release (\( \dagger\dagger \), \( P < 0.01 \); \( \dagger\dagger\dagger \), \( P < 0.001 \)) were calculated using logIC\(_{50}\) values by unpaired Student’s t test.

<table>
<thead>
<tr>
<th>Drug</th>
<th>Transmitter</th>
<th>( -\text{Ca}^{2+} ) Potency (IC(_{50}))</th>
<th>( +\text{Ca}^{2+} ) Potency (IC(_{50}))</th>
<th>( \text{Ca}^{2+})-Dependent Potency (IC(_{50}))</th>
</tr>
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<tbody>
<tr>
<td>Isoflurane</td>
<td>Glutamate</td>
<td>0.58 ± 0.10 mM( * ) 0.57 ± 0.04 mM( ** ) 0.58 ± 0.06 mM( *** ) 1.06 ± 0.04 mM( \dagger\dagger )</td>
<td>0.26 ± 0.06 mM 0.78 ± 0.03 mM 1.06 ± 0.04 mM( \dagger\dagger )</td>
<td>0.26 ± 0.06 mM 0.78 ± 0.03 mM 1.06 ± 0.04 mM( \dagger\dagger )</td>
</tr>
<tr>
<td>Enflurane</td>
<td>Glutamate</td>
<td>0.64 ± 0.12 mM( ** ) 0.67 ± 0.06 mM( ** ) 0.72 ± 0.11 mM( ** ) 2.34 ± 0.29 mM( \dagger\dagger\dagger )</td>
<td>0.31 ± 0.05 mM 1.48 ± 0.14 mM 2.34 ± 0.29 mM( \dagger\dagger\dagger )</td>
<td>0.31 ± 0.05 mM 1.48 ± 0.14 mM 2.34 ± 0.29 mM( \dagger\dagger\dagger )</td>
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<tr>
<td>Halothane</td>
<td>Glutamate</td>
<td>0.33 ± 0.04 mM( ** ) 0.41 ± 0.04 mM( ** ) 0.47 ± 0.06 mM( ** ) 0.76 ± 0.08 mM( \dagger\dagger )</td>
<td>0.33 ± 0.04 mM( ** ) 0.41 ± 0.04 mM( ** ) 0.47 ± 0.06 mM( ** ) 0.76 ± 0.08 mM( \dagger\dagger )</td>
<td>0.33 ± 0.04 mM( ** ) 0.41 ± 0.04 mM( ** ) 0.47 ± 0.06 mM( ** ) 0.76 ± 0.08 mM( \dagger\dagger )</td>
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<tr>
<td>Tetrodotoxin</td>
<td>Glutamate</td>
<td>20 ± 58 nM( \dagger\dagger ) 18 ± 5.5 nM 18 ± 6.9 nM 15 ± 8.3 nM</td>
<td>29 ± 28 nM</td>
<td>29 ± 28 nM</td>
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<tr>
<td>Tetrodotoxin</td>
<td>GABA</td>
<td>29 ± 28 nM</td>
<td>28 ± 7.3 nM</td>
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presynaptic GABA<sub>A</sub> receptor subtypes, modulation by endogenous and exogenous factors (Cherubini and Conti, 2001), and tetrodotoxin-insensitive nicotinic-mediated increases in GABA release (Zhu and Chiappinelli, 2002) suggest possible mechanisms for transmitter-selective anesthetic effects.

Other potential presynaptic targets of volatile anesthetics include K<sup>+</sup> and Ca<sup>2+</sup> channels (Topf et al., 2003; Franks and Honoré, 2004), ligand-gated ion channels (Franks and Lieb, 1994), cell signaling machinery, such as protein kinase C (Hemmings and Adamo, 1998) and G-protein coupled receptors (Yamakura et al., 2001), and synaptic vesicle fusion machinery (Hawasli et al., 2004), all of which can modulate transmitter release (Miller, 1998; Engelman and MacDermott, 2004). Genetic inactivation of components of the presynaptic release machinery differentially affect basal and evoked release (SNAP-25; Washbourne et al., 2001) or evoked glutamate and GABA release (Munc 13-1; Augustin et al., 1999), suggesting these proteins as potential targets for the pathway and transmitter-selective effects of volatile anesthetics. Like Na<sup>+</sup> channels, these putative anesthetic targets may have distinct patterns of expression within and between neurons that may contribute to transmitter-selective effects.

Preferential inhibition of Ca<sup>2+</sup>-independent 4AP-evoked GABA versus glutamate release by isoflurane and enflurane, but not halothane, was in contrast to preferential inhibition of Ca<sup>2+</sup>-dependent glutamate versus GABA release by all three anesthetics tested. This suggests more than one presynaptic site of action for these effects. A potential target for anesthetic effects on Ca<sup>2+</sup>-independent transmitter release is inhibition of reverse transmitter transporter function (Attwell et al., 1993). Inhibition by isoflurane of glutamate uptake into rat cerebrocortical synaptosomes occurs with similar potency (IC<sub>50</sub> = 0.7 mM) to inhibition of Ca<sup>2+</sup>-independent release, but inhibition of GABA uptake (IC<sub>50</sub> = 0.8 mM) is less potent than inhibition of Ca<sup>2+</sup>-independent release (Westphalen and Hemmings, 2003b). The maximal efficacy of isoflurane inhibition of glutamate and GABA uptake also varies (Westphalen and Hemmings, 2003b), consistent with a greater role of transporter inhibition to glutamate release than GABA release. In view of the insensitivity of GABA uptake to volatile anesthetics, the greater sensitivity of Ca<sup>2+</sup>-independent 4AP-evoked GABA release to isoflurane further suggests that nerve-terminal GABA transporters are not sensitive to volatile anesthetics.

In summary, three volatile anesthetics consistently inhibited Ca<sup>2+</sup>-dependent 4AP-evoked glutamate release with greater potency than GABA release, which supports distinct presynaptic targets between glutamatergic and GABAergic nerve terminals. Although glutamate is released from synaptic vesicles at saturating concentrations for its receptors, even moderate reductions in release probability could affect the kinetics of synaptic glutamate concentration (Cavelier et al., 2005) and the release probability of low probability nerve terminals (Prakriya and Mennerick, 2000) to depress excitatory transmission. The less potent inhibition of GABA release by volatile anesthetics is balanced by postsynaptic potentiation of GABA<sub>A</sub> receptors, such that net inhibitory GABAergic transmission is enhanced (Stucke et al., 2002). The correlation between anesthetic potency in vivo (MAC) and potency of evoked glutamate release inhibition supports this action as a relevant volatile anesthetic target. The differing potencies for inhibition of Ca<sup>2+</sup>-dependent and Ca<sup>2+</sup>-inde-
Volatile Anesthetics Inhibit Evoked Amino Acid Release

excitatory and enhance net inhibitory central nervous system mechanisms by which volatile anesthetics may depress

References


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