Mechanisms of Inhibition of T-Type Calcium Current in the Reticular Thalamic Neurons by 1-Octanol: Implication of the Protein Kinase C Pathway

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ABSTRACT

Recent studies indicate that T-type calcium channels (T-channels) in the thalamus are cellular targets for general anesthetics. Here, we recorded T-currents and underlying low-threshold calcium spikes from neurons of nucleus reticularis thalami (nRT) in brain slices from young rats and investigated the mechanisms of their modulation by an anesthetic alcohol, 1-octanol. We found that 1-octanol inhibited native T-currents at subanesthetic concentrations with an IC50 of approximately 4 μM. In contrast, 1-octanol was up to 30-fold less potent in inhibiting recombinant CaV3.3 T-channels heterologously expressed in human embryonic kidney cells. Inhibition of both native and recombinant T-currents was accompanied by a hyperpolarizing shift in steady-state inactivation, indicating that 1-octanol stabilized inactive states of the channel. To explore the mechanisms underlying higher 1-octanol potency in inhibiting native nRT T-currents, we tested the effect of the protein kinase C (PKC) activator phorbol 12-myristate 13-acetate (PMA) and PKC inhibitors. We found that PMA caused a modest increase of T-current, whereas the inactive PMA analog 4α-PMA failed to affect T-current in nRT neurons. In contrast, 12-(2-cyanoethyl)-6,7,12,13-tetrahydro-13-methyl-5-oxo-5H-indolo[2,3-a]pyrrolo[3,4-c]-carbazole (Go 6976), an inhibitor of calcium-dependent PKC, decreased baseline T-current amplitude in nRT cells and abolished the effects of subsequently applied 1-octanol. The effects of 1-octanol were also abolished by chelation of intracellular calcium ions with 1,2-bis(2-aminophenoxy)ethane-N,N,N′,N′′-tetraacetic acid. Taken together, these results suggest that inhibition of calcium-dependent PKC signaling is a possible molecular substrate for modulation of T-channels in nRT neurons by 1-octanol.

Multiple subtypes of neuronal voltage-gated Ca2+ channels have a key function in controlling cellular excitability and transmitter release. The proposed functions of low-voltage-activated or transient (T-type) Ca2+ channels (T-channels) include promotion of Ca2+-dependent burst firing, generation of low-amplitude intrinsic neuronal oscillations, elevation of Ca2+ entry, and boosting of dendritic signals.

These functions of T-currents in thalamic circuitry may contribute to pacemaker activity, wakefulness and sleep cycles, and seizure susceptibility (Llinás, 1988; Perez-Reyes, 2003). We have shown previously that volatile general anesthetics at clinically relevant concentrations block recombinant and native T-current variants in peripheral and central neurons (Todorovic and Lingle 1998; Todorovic et al., 2000; Joksovic et al., 2005a,b). T-channels are abundantly expressed in thalamic nuclei, where they are crucial in control of the functional states of those neurons (McCormick and Bal, 1997; Llinás et al., 1998). Furthermore, inhibition of thalamic signaling has been implicated as a possibly common mechanism that contributes to such clinical effects of anesthetics as loss of consciousness and sedation (Alkire et al., 2000; Rudolph and Antkowiak, 2004). Therefore, the potential function of T-channels in the thalamus as targets for the action of general anesthetics could be of great significance in the study of consciousness and sedation.

ABBREVIATIONS: T-channel, transient (T-type) Ca2+ channel; LTS, low-threshold Ca2+ spikes; nRT, reticular thalamic nucleus; HEK, human embryonic kidney; I-V, current-voltage; TTX, tetrodotoxin; PMA, phorbol 12-myristate 13-acetate; Go 6976, 12-(2-cyanoethyl)-6,7,12,13-tetrahydro-13-methyl-5-oxo-5H-indolo[2,3-a]pyrrolo[3,4-c]-carbazole; BAPTA, 1,2-bis(o-aminophenoxy)ethane-N,N′,N′′,N′′′-tetraacetic acid; PKC, protein kinase C.
eral anesthetics remains an important issue in our understanding of the cellular mechanisms of anesthetic action.

Many normal alcohols have anesthetic capacity and are widely used to probe for molecular targets of anesthesia. Of particular interest for our studies is 1-octanol, which is a general anesthetic with estimated aqueous concentration EC50 values ranging from 57 to 130 μM for loss of righting reflex in tadpoles (Alifimoff et al., 1989). Within the same concentration range, 1-octanol may potentiate GABA<sub>A</sub>-receptor-gated currents, one of the major cellular targets of general anesthesia (Franks and Lieb, 1994). However, 1-octanol within the same concentration range also inhibits T-current in native systems, including adult dorsal root ganglion cells (Todorovic and Lingle, 1998), GH<sub>3</sub> cell lines (Herrington and Lingle, 1992), hippocampal neurons (Takahashi et al., 1989), and thalamic relay neurons (Llinás et al., 2007). Moreover, we have demonstrated that 1-octanol completely blocks recombinant Ca<sub>V</sub>3.1 (α1G) and Ca<sub>V</sub>3.2 (α1H) T-channels, with estimated IC<sub>50</sub> values of 160 and 220 μM, respectively (Todorovic et al., 2000). Given the proposed importance of the thalamus in sensory processing and anesthetic states, we examined the effect of 1-octanol, a representative anesthetic alcohol, on T-current and underlying low-threshold Ca<sup>2+</sup> spikes (LTS) in the reticular thalamic nucleus (nRT), the main inhibitory structure in the thalamus.

Materials and Methods

In Vitro Tissue Slice Preparation. We did most of these experiments on transverse rat brain slices cut through the middle anterior portion of the nRT (Paxinos and Watson, 1982) at a thickness of 250 to 300 μm, as we have done previously (Joksovic et al., 2005a,b, 2006, 2007). Gravid Sprague-Dawley rats were housed in a local animal facility in accordance with protocols approved by the University of Virginia Animal Use and Care Committee. We adhered to the guidelines in the Guide for the Care and Use of Laboratory Animals (Institute of Laboratory Animal Resources, 1996).

At the age of 7 to 14 days, rats of either sex were anesthetized with isoflurane and decapitated. The brains were rapidly removed and placed in chilled (4°C) cutting solution consisting of 2 mM CaCl<sub>2</sub>, 260 mM sucrose, 26 mM NaHCO<sub>3</sub>, 10 mM glucose, 3 mM KCl, 1.25 mM Na<sub>2</sub>HPO<sub>4</sub>, and 2 mM MgCl<sub>2</sub> equilibrated with a mixture of 95% O<sub>2</sub> and 5% CO<sub>2</sub>. We glued a block of tissue containing the thalamus to the chuck of a motorized vibrissome (WPI, Saratoga, FL) and cut slices in a transverse plane. We incubated the slices in 36°C oxygenated saline for 1 h, then placed them in a recording chamber that was superfused at a rate of 1.5 ml/min with 124 mM NaCl, 4 mM KCl, 26 mM NaHCO<sub>3</sub>, 1.25 mM Na<sub>2</sub>HPO<sub>4</sub>, 2 mM MgCl<sub>2</sub>, 10 mM glucose, and 2 mM CaCl<sub>2</sub> equilibrated with a mixture of 95% O<sub>2</sub> and 5% CO<sub>2</sub>. Slices were maintained in the recording chamber at room temperature on room air, where they remained viable for at least 1 h.

Recording Procedures. The extracellular saline solution typically used for recording in voltage-clamp and current-clamp experiments consisted of 2 mM CaCl<sub>2</sub>, 130 mM NaCl, 2.5 mM MgCl<sub>2</sub>, 10 mM glucose, 26 mM Na<sub>2</sub>HPO<sub>4</sub>, 1.25 mM NaHCO<sub>3</sub>, and 0.001 mM tetrodotoxin (TTX). This was equilibrated with a mixture of 95% O<sub>2</sub> and 5% CO<sub>2</sub> for at least 30 min with final pH of 7.35 to 7.45. In some current-clamp experiments, TTX was omitted to study spike firing of mNT neurons. For recording T-currents in brain slices, we used an internal solution of 135 to 140 mM tetramethylammonium hydroxide (TMA-OH), 10 mM EGTA, 40 mM HEPEs, and 2 mM MgCl<sub>2</sub> titrated to pH 7.15 to 7.25 with hydrofluoric acid (HF) (Todorovic and Lingle 1998). In some experiments, we altered this internal solution by substituting BAPTA for EGTA. Recording electrodes for current-clamp studies contained 130 mM KCl, 5 mM MgCl<sub>2</sub>, 1 mM EGTA, 40 mM Na-HEPES, 2 mM MgATP, and 0.1 mM Na<sub>2</sub>GTP at pH 7.2. For the data presented, membrane potential values were not corrected for the measured liquid junction potential of −10 mV in voltage-clamp experiments or for the potential of −5 mV in current-clamp experiments.

All recordings were obtained from thalamic neurons visualized with an infrared differential interference contrast camera (C2400; Hamamatsu, Hamamatsu City, Japan) on the Zeiss 2 FS Axoscope (Jena, Germany) with a 40×/0.8 lens and patch-clamp pipette using a micromanipulator (MP-285; Sutter Instrument, Novato, CA).

Recombinant Human Embryonic Kidney Cells. HEK 293 cells were stably transfected with rat α1B (Ca<sub>V</sub>3.3.b) constructs as described previously (Murbartia et al., 2002; Joksovic et al., 2005b). Cells were typically used 1 to 2 days after plating. The standard extracellular saline for recording Ca<sup>2+</sup> current contained 160 mM tetroethylammonium-Cl, 10 mM HEPEs, and 2 mM CaCl<sub>2</sub>, adjusted to pH 7.4 with tetroethylammonium-OH. The internal solution consisted of 110 mM Cs-methane sulfonate, 14 mM phosphocreatine, 10 mM HEPEs, 1 or 9 mM EGTA, 5 mM Mg-ATP, and 0.3 mM Tris-GTP; the pH was adjusted to 7.15 to 7.20 with CsOH (standard osmolality, 300 mOsm). All recordings of currents from HEK 293 cells were done using an inverted Zeiss 200 Axiovert microscope (Jena, Germany) with a 40× lens.

Electrophysiological Recordings. Recordings were made with standard whole-cell voltage-clamp technique (Hamill et al., 1981). Electrodes were fabricated from thin-walled microcapillary tubes (Drummond Scientific, Broomall, PA) and had final resistances of 3 to 6 MΩ. We recorded membrane currents with an Axocampl 200B patch-clamp amplifier (Axon Instruments, Foster City, CA). Voltage commands and the digitization of membrane currents were done with Clampex 8.2 of the pClamp software package (Molecular Devices, Foster City, CA). Neurons were typically held (V<sub>H</sub>) at −90 mV and depolarized to test potential (V<sub>test</sub>) of −50 mV every 10 to 20 s to evoke inward Ca<sup>2+</sup> currents. Data were analyzed using Clampfit (Molecular Devices) and Origin 7.0 (OriginLab Corp, Northampton, MA). We filtered currents at 5 to 10 kHz and typically compensated for 50 to 80% of series resistance (R<sub>s</sub>). In most experiments, a P/5 protocol was used for on-line leakage subtraction.

Analysis of Current Inhibition. The percentage reduction in peak T-current at a given 1-octanol concentration was used to generate concentration-response curves. For each such curve, all points are averages of multiple determinations obtained from at least five different cells. In most of the recombinant cells, we tested at least two different concentrations of 1-octanol, whereas in intact brain slices, only one concentration was used per cell in a given slice. On all plots, vertical bars indicate standard errors of the means (S.E.M.). Mean values on concentration-response curves were fit to the following function: PB/(1-10<sup>−50</sup>) = PB<sub>max</sub>/((1 + (IC<sub>50</sub>/1-10<sup>−50</sup>))<sup>n<sub>H</sub></sup>), where PB<sub>max</sub> is the maximal percentage inhibition of peak T-current, IC<sub>50</sub> is the concentration that produces 50% of maximal inhibition, and n<sub>H</sub> is the apparent Hill coefficient for inhibition. Fitted values are typically reported with 95% linear confidence limits.

Analysis of Current. The voltage dependence of steady-state activation was described with a single Boltzmann distribution: G(V) = G<sub>max</sub>/((1 + exp(−(V − V<sub>50</sub>)/k))), where G<sub>max</sub> is the maximal estimated conductance, V<sub>50</sub> is the half-maximal voltage, and k (mV) represents the voltage dependence of the distribution. The voltage-dependence of steady-state inactivation was described with a single Boltzmann distribution: I(V) = I<sub>max</sub>/((1 + exp(−(V − V<sub>50</sub>)/k))), where I<sub>max</sub> is the maximal current, V<sub>50</sub> is the half-maximal voltage, and k (mV) represents the voltage dependence of the distribution. The time course of current inactivation was fitted using a single exponential function, f(t) = A<sub>1</sub>exp(−t/τ<sub>1</sub>), yielding one-time constants (τ<sub>1</sub>) and their amplitude (A<sub>1</sub>).

For all current-voltage (I-V) curves and steady-state inactivation curves, fitted values were typically reported with 95% linear confidence limits. Input resistance (R<sub>in</sub>) was determined from the slope of the peak voltage versus the current plot that resulted from injecting.
80- to 160-ms current ranging from 100 to 1000 pA. Statistical analysis was performed with either paired Student’s t test or unpaired Student’s t test where appropriate, with statistical significance at p < 0.05.

Methodological Considerations Relevant to Intact Brain Slices. Recordings from intact brain slices offer great advantages for studying neurons in an intact setting in vitro. However, because voltage control is compromised in whole-cell recordings from slices because of the presence of extensive cell processes, we paid close attention to the signs of good voltage control. Specifically, there was no extensive delay in the onset of current; also, the onset and offset kinetics depended on voltage, not on the amplitude of current. In whole-cell experiments, because intact nRT neurons have long processes, rapid components of recorded current, such as fast-activation kinetics or tail currents, are not likely to reflect the true amplitude of the phenomenon. Because of the presence of extensive cell processes, we measured these current components using the whole-cell configuration of the recording amplifier, and extensively delayed the onset and offset times of the current, which is consistent with the partial blockage of these processes by the whole-cell configuration.

To facilitate application of drugs, we applied first 10 ml of external solution containing drug with bath flow of approximately 5 ml/min, and then continued with perfusion of 1 to 2 ml/min. All drugs were applied until an apparent steady-state effect on peak T-current was achieved. To avoid the accumulation of highly lipophilic substance in the tissue, we used only a single application of any given concentration of 1-octanol per slice.

Drugs and Chemicals. TTX was obtained from Alomone Lab (Jerusalem, Israel). All other salts and chemicals were obtained from Sigma Chemical (St. Louis, MO). Stock solutions (100 μM) of phorbol 12-myristate 13-acetate (PMA) and its inactive stereoisomer (4a-PMA), as well as GO 6976 at 10 mM, were made in dimethyl sulfoxide, while a 100 μM stock solution of TTX was prepared in distilled water. The maximal final concentration of dimethyl sulfoxide used in our experiments was 0.1%, which does not significantly affect native thalamic Ca2+ currents (Joksovic et al., 2005a,b).

Solutions. Multiple independently controlled glass syringes attached to the common PVC tubing served as reservoirs for a gravity-driven perfusion system. Manually controlled valves were used to switch solutions. All experiments were done at room temperature (20–24°C). All drugs were prepared as stock solutions kept in sealed glass vials and freshly diluted to appropriate concentrations as needed. 1-Octanol was prepared from 2 mM stock solution obtained from Sigma Chemical (St. Louis, MO). Stock solutions (100 μM) of phorbol 12-myristate 13-acetate (PMA) and its inactive stereoisomer (4a-PMA), as well as GO 6976 at 10 mM, were made in dimethyl sulfoxide, while a 100 μM stock solution of TTX was prepared in distilled water. The maximal final concentration of dimethyl sulfoxide used in our experiments was 0.1%, which does not significantly affect native thalamic Ca2+ currents (Joksovic et al., 2005a,b).

Results

Fig. 1. Potent inhibition of native slowly inactivating T-currents in nRT neurons by 1-octanol. A, traces represent T-current elicited from Vh = −90 mV to Vf = −50 mV in a representative nRT neuron before and after (black lines) as well as during (gray line) the application of 10 μM 1-octanol. This resulted in depression of the current amplitude but had no apparent effect on the macroscopic kinetics of the current. B, symbols represent the time course of the effect on peak T-current before, during, and after the application of 1-octanol to the same cell as that in A. Depolarizing pulse was applied every 10 s; the horizontal bar indicates time of the application. Inhibition of the peak current is gradual and partially reversible. C, concentration-response curve for T-current inhibition by 1-octanol. The solid symbols indicate the average of multiple determinations (n = 5 or more); vertical lines are ± S.E.M. (visible only if bigger than symbols). The solid line represents the best fit of the Hill equation. The fitted value for the curve is IC50 of 4 ± 1 μM, nHill = 1.6 ± 0.5; maximal fitted effect was constrained to 100% inhibition.

Both application of 1-octanol potently inhibited T-current in nRT cells in brain slices that display characteristic slowly inactivating kinetics (Joksovic et al., 2005a,b). Figure 1A shows traces and Fig. 1B depicts the time course from the same voltage-clamp experiment in which 10 μM 1-octanol reversibly inhibited approximately 80% of the peak T-current without an apparent effect on macroscopic current inactivation kinetics. Figure 1C summarizes average data points with 1, 3, 5, and 10 μM 1-octanol demonstrating concentration-dependent, potent, and almost complete inhibition of T-current. The solid line represents a Hill plot giving an estimated IC50 of approximately 4 μM.

We hypothesized that 1-octanol may abolish LTS of nRT neurons that critically depend on T-channels. Thus, we used current-clamp recordings from these cells and assessed spike firing when the neuronal membrane was depolarized with current injections through the recording electrode from holding negative membrane potentials (e.g., −90 mV), which maximize the availability of T-channels. Figure 2A presents traces from a representative nRT cell before, during, and...
after the application of 10 μM 1-octanol. 1-Octanol reversibly depressed the number of action potentials that crowned LTS from four to one. The histograms in Fig. 2B indicate that in similar current-clamp experiments, 10 μM 1-octanol significantly decreased the membrane firing that accompanied LTS from approximately five to three action potentials (n = 6 cells, p < 0.05). Even though in most of the cells applications of 1-octanol in current-clamp experiments caused changes in baseline membrane potential, overall average changes did not significantly differ between baseline (−54.3 ± 3.2 mV) and 1-octanol (−51.0 ± 5.3 mV, n = 6, p > 0.05, data not shown).

In another set of experiments, we included TTX in the external solution and applied a 100-ms preceding hyperpolarizing pulse, which resulted in rebound LTS, because sufficient hyperpolarization of the neuronal membrane caused deinactivation of T-channels. This protocol allowed us to measure the effects of 1-octanol on isolated LTS and input resistance in current-clamp experiments (Joksovic et al., 2006). On average, 10 μM 1-octanol decreased the amplitude of isolated LTS in nRT neurons for 35 ± 5% (n = 5, p < 0.01, data not shown). In contrast, average input resistance (R\textsubscript{in}) was not significantly affected in these cells (control, 118 ± 2 MΩ; 1-octanol, 162 ± 60 MΩ; n = 6, p > 0.05, data not shown). Somewhat greater 1-octanol-induced inhibition of isolated T-currents than LTSs and associated burst firing may be related to better separation of T-currents from other ionic conductances in voltage-clamp experiments.

Next we considered the possibility that potent inhibition of native T-current in nRT neurons by 1-octanol may be due to its direct interaction with a specific molecular isoform of T-channels that is expressed in this thalamic nucleus. Previous molecular studies using in situ hybridization demonstrated that nRT has abundant transcripts for Ca\textsubscript{V}3.2 (α1H) and Ca\textsubscript{V}3.3 (α1I), but sparse Ca\textsubscript{V}3.1 (α1G) isoforms of the pore-forming α1 subunit (Talley et al., 1999). Thus, we also examined the sensitivity of recombinant rat Ca\textsubscript{V}3.3 channels, which characteristically display slow inactivation kinetics similar to those of T-currents of native nRT cells (Joksovic et al., 2005b).

Figure 3A shows traces of inhibition of recombinant Ca\textsubscript{V}3.3 current in HEK 293 cells with escalating concentrations of 1-octanol (30, 100, 300, and 1000 μM). Figure 3B shows the time course from the same cell. Here, 1-octanol rapidly induced a reversible, almost complete concentration-dependent inhibition of Ca\textsubscript{V}3.3 current. However, the black solid line representing the Hill plot of the average concentration-response curve in Fig. 3C shows that this agent was more than 30-fold less potent in inhibiting recombinant Ca\textsubscript{V}3.3 (IC\textsubscript{50}, 150 μM) than native nRT T-currents (solid gray line; IC\textsubscript{50}, 4 μM). The dashed black line in Fig. 3C represents the Hill plot of the 1-octanol block of recombinant human Ca\textsubscript{V}3.2 channels with an IC\textsubscript{50} of 219 μM (from Todorovic et al., 2000). Most of our recordings with recombinant cells were done in intracellular solution containing 10 mM EGTA. Hence, we also examined the ability of 100, 300, and 1000 μM 1-octanol to inhibit recombinant Ca\textsubscript{V}3.3 currents with 1 mM intracellular EGTA to provide more physiological concentrations of intracellular Ca\textsuperscript{2+} (Harney et al., 2006). However, in these experiments with low concentrations of EGTA we obtained similar potency of 1-octanol in inhibiting peak Ca\textsubscript{V}3.3 current (fitted IC\textsubscript{50}, 176 ± 1.0 μM; n\textsubscript{HT}, 1.4 ± 0.1, n = 6 cells; data not shown).

Fig. 3. 1-Octanol inhibits burst firing and LTS in nRT cells. A, representative traces recorded in current-clamp mode from an nRT neuron at a holding potential of −93 mV, indicated by the horizontal dashed line. LTS was evoked on injection of a small depolarizing pulse (duration, 160 ms; amplitude, 60 pA) and elicited a burst of 4 action potentials (APs). This burst was greatly diminished in the presence of 10 μM 1-octanol (one AP), but was completely recovered on washout of 1-octanol (four APs). Bars indicate calibration. Holding potential was maintained by a constant injection of current via the recording electrode. B, the histogram compares the number of AP spikes in control (4.8 ± 1.0) and in the presence of 1-octanol (3.0 ± 1.0). *, p < 0.05 (n = 6 cells, paired Student’s t test). Vertical bars represent S.E.

Thus, it seems that inhibitory effect of 1-octanol on recombinant Ca\textsubscript{V}3.3 currents is not critically dependent on intracellular Ca\textsuperscript{2+} concentrations.

In contrast to the effect of 1-octanol on native T-current in nRT cells, traces on Fig. 3A with 100 and 300 μM 1-octanol suggest that 1-octanol enhances the speed of macroscopic current inactivation. Thus, we also considered the effect of 1-octanol on nRT current inactivation. We did biophysical studies to discern possible differences in the mechanisms of modulation of nRT and Ca\textsubscript{V}3.3 T-type currents that could account for the higher potency of the inhibition of native currents by 1-octanol. Figure 4A shows a...
Fig. 3. 1-Octanol inhibits recombinant T-currents less potently than do native nRT T-currents. A, traces depict the inhibitory effect of escalating concentrations of 1-octanol on the amplitude of CaV3.3 current in a representative HEK 293 cell (V_h = −90 mV, V_m = −30 mV). A progressive increase in concentrations of 1-octanol leads to almost complete inhibition of T-current amplitude and apparent speeding of current inactivation kinetics. B, time course of T-current inhibition with 30, 100, 300, and 1000 μM 1-octanol from the same cell as that in A. Horizontal bars indicate the duration of drug application. Note rapid onset and almost complete washout of the effect after each application. A depolarizing test pulse was applied every 20 s. C, symbols indicate the concentration-response curve for CaV3.3 T-type current inhibition by 1-octanol. The solid symbols indicate the average of multiple determinations (n = 5 or more); vertical lines are ± S.E.M. (visible only if bigger than symbols). The solid black line represents the best fit of the Hill equation for CaV3.3. The fitted value for the curve is IC_{50} of 149.4 ± 35.6 μM, n_H = 1.3 ± 0.4; maximal fitted effect was constrained to 100% inhibition. The solid gray line is the same as that in Fig. 1C, indicating that native T-current in nRT cells is 30-fold more potently inhibited by 1-octanol than recombinant CaV3.3 current. The dashed line represents the best fit of the Hill equation for CaV3.2 current (from Todorovic et al., 2000) yielding an IC_{50} of 219 μM, n_H = 1.4; curve fit was constrained to 100% inhibition. D, the steady-state inactivation kinetics of T-currents in CaV3.3-transfected HEK cells were examined by paired-pulse protocols at different conditioning potentials. Double-pulse protocols to −30 mV were used to elicit T-currents, separated by 3.5-s prepulse to potentials ranging from −110 to −40 mV before (filled symbols) and during (open symbols) the application of 300 μM 1-octanol. The data were best fitted with the Boltzmann equation, yielding V_{1/2} of −64.5 ± 0.3 mV (k = 7.4 ± 0.3 mV) in control and −74.2 ± 0.4 mV (k = 8.0 ± 0.3 mV) in the presence of 1-octanol (n = 5 cells). E, the average I-V relationships before and during the application of 300 μM 1-octanol. Currents were elicited by progressing from −80 to 30 mV in 5-mV increments from a holding potential of −90 mV (n = 6 cells). Note the depression of the current amplitude at most potentials and the slight shift of the I-V curve to the right in the presence of 1-octanol. F, normalized conductance in whole-cell recordings from current-voltage experiments depicted in E of this figure. The average half-conductance (V_{1/2}) was in control −47.2 ± 0.4 mV (k = 3.2 ± 0.3 mV) and in the presence of 1-octanol −40.4 ± 0.4 mV (k = 7.1 ± 0.4 mV). Fits were done using the Boltzmann equation. The estimated reversal potential was taken to be 50 mV.

Fig. 4. The effects of 1-octanol on the kinetic properties of T-currents in nRT neurons. A, a family of raw T-current traces in a representative nRT cell elicited with test potentials from −70 to −50 mV in 5-mV increments from a holding potential of −90 mV in control conditions (top traces) and in the presence of 5 μM 1-octanol in external solution (bottom traces). Bars indicate calibration. B, the average I-V relationships before and during the application of 5 μM 1-octanol. Currents were elicited by progressing from −80 to −20 mV in 5-mV increments from a holding potential of −90 mV (n = 5 cells). Note the depression of the current amplitude at most potentials and the slight shift of the I-V curve to the right in the presence of 1-octanol. C, normalized conductance in whole-cell recordings from current-voltage experiments depicted in B. 1-Octanol shifted half-conductance (V_{1/2}) to the right from −67.2 ± 0.4 mV (k = 2.4 ± 0.4 mV) in control to −63.5 ± 2.5 mV (k = 5.7 ± 2.6 mV). Fits were done using the Boltzmann equation. D, the steady-state inactivation kinetics of T-currents in nRT neurons were examined by paired-pulse protocols at different conditioning potentials. Double-pulse protocols to −50 mV were used to elicit T-currents separated by 3.5-s prepulse to potentials ranging from −110 to −50 mV in 5-mV increments before (filled symbols) and during (open symbols) the application of 1-octanol. The data were best fitted with the Boltzmann equation, yielding V_{1/2} of −88.0 ± 0.2 mV (k = 5.0 ± 0.1 mV) in control and −99.6 ± 0.2 mV (k = 3.7 ± 0.2 mV) in the presence of 1-octanol (n = 10 cells).
1-octanol, −62.5 ± 2.0 mV; n = 5, p > 0.05). It is noteworthy that 1-octanol had a significant voltage-dependent effect on steady-state inactivation, shifting midpoint of inactivation $V_{50}$ to hyperpolarized potentials by approximately 12 mV (Fig. 4D). In average, in control conditions $V_{50}$ occurred at −87.8 ± 2.0 mV, and in the presence of 1-octanol in the same cells $V_{50}$ was shifted to −100 ± 1.0 mV (n = 10, p < 0.001). This was much like its effect in recombinant Ca$_{v}$3.3 channels.

Based on our results, we conclude that potent inhibition of native nRT currents by 1-octanol cannot be entirely explained either by a direct interaction with a particular known isoform of T-channels or specific biophysical features of channel block. Thus, we considered the possibility that 1-octanol interacts with second messengers in intact nRT neurons. Protein kinase C (PKC), an important signaling molecule, has been proposed as the putative target of general anesthesia (Hemmings 1998; reviewed in Rebecchi and Pentyala, 2002). Previous data from other systems indicate that 1-octanol and related normal alcohols may either stimulate (Shen et al., 1999) or inhibit (Slater et al., 1993) the activity of PKC. Thus, we tested the ability of PKC activators and inhibitors to alter the baseline T-currents in nRT cells and to consequently affect the ability of 1-octanol to inhibit T-currents.

In these set of experiments, we first applied PKC activator, 300 nM PMA to nRT neurons. Figure 5A shows traces from a representative neuron. PMA caused a small (approximately 17%) increase in baseline peak T-current without obvious changes in current kinetics. In a control experiment, 4α-PMA, an inactive form of PMA, had a minimal effect on baseline T-current at the same concentrations (Fig. 5B). Overall, we found that 300 nM PMA increased baseline T-current in nRT cells by 16 ± 3% (p < 0.001, n = 7), whereas 300 nM 4αPMA had no significant effect on baseline T-current in these cells (6 ± 5% increase, p > 0.05, n = 5).

Our data are consistent with a modest stimulation of baseline T-current in nRT cells by PKC activation. However, because 1-octanol consistently inhibited T-currents in these cells, it is unlikely that its effects are mediated by PKC stimulation. We reasoned that if 1-octanol inhibits PKC in nRT cells, pharmacological or physiological inhibitors of PKC would also inhibit baseline T-current in nRT and interfere with the activity of 1-octanol to modulate this current. Molecular studies with in situ hybridization indicate that both calcium-dependent and Ca$^{2+}$-independent isoforms of PKC have been expressed in the thalamus (Minami et al., 2000). To probe for the importance of Ca$^{2+}$ ions in mediating 1-octanol inhibition of T-current in nRT cells, we used BAPTA, a high-affinity chelator of Ca$^{2+}$ ions, that at physiological pH buffers Ca$^{2+}$ approximately 100-fold faster than EGTA and can diminish cytosolic Ca$^{2+}$ fast enough to suppress a biological response in the brain slices (Harney et al., 2006). Hence, we dialyzed BAPTA into cells via recording pipette solution at a high concentration of 10 mM. We used only nRT cells that had been dialyzed for at least 10 min to assure diffusion of BAPTA into dendritic regions. In the cells that still had significant T-currents under these recording conditions, we found that BAPTA completely abolished the ability of 10 μM 1-octanol to inhibit T-currents (2 ± 1% block, p > 0.05, n = 5). Figure 6A shows traces (left) and the time course of T-current (right) from a representative nRT neuron in the presence of BAPTA in internal solution. Furthermore, Fig. 6B shows that short-term application of 10 μM Go 6976, a specific Ca$^{2+}$-dependent PKC inhibitor, decreased baseline T-current amplitude approximately 40%, whereas subsequently coapplied 10 μM 1-octanol inhibited less than 10% of T-current amplitude. The histograms in Fig. 6C summarize average data obtained when Go 6976 and 1-octanol were coapplied to the same cells. Overall, 1-octanol had no significant effect on baseline T-current in nRT cells treated with Go 6976 (n = 5, p > 0.05). In contrast, when we applied 10 μM Go 6976 on recombinant HEK 293 cells expressing Ca$_{v}$3.3 channels, there was no statistically significant effect on peak T-current amplitude (1 ± 6% change, n = 3, p > 0.05; data not shown). Thus, it seems that baseline native and recombinant T-currents are differently regulated and that the effects of 1-octanol on nRT currents are at least partly mediated by the inhibition of Ca$^{2+}$-dependent PKC pathway.

Discussion

The major finding of our study is that the anesthetic alcohol 1-octanol induced a potent concentration-dependent inhibition (IC$_{50}$, 4 μM) of native slowly inactivating T-currents and underlying burst firing in nRT neurons in intact brain slices. These effects could be important for the sedative and hypnotic action of anesthetic alcohols, because the in vitro effect of 1-octanol in nRT neurons was well within the concentrations necessary to induce loss of righting reflex in the tadpole anesthesia assay (Alifimoff et al., 1989). That assay is frequently used to estimate hypnotic properties of various drugs, because its results generally correlate well with measures of anesthetic potency in mammals (Franks and Lieb, 1994). The inhibitory effect of 1-octanol on T-channel-depen-
dent LTS and neuronal burst firing in nRT neurons (this study) and thalamo-cortical relay neurons (Soltész et al., 1991; Llinás et al., 2007) could at least contribute to the inhibitory effect of anesthetics on neuronal firing in the thalamo-cortical sensory pathway. Such inhibitory effect on thalamo-cortical circuitry is observed during in vivo anesthesia with other general anesthetics (Angel, 1991; Detesch et al., 2002). The effect of 1-octanol on LTS and burst firing of thalamic neurons in brain slices is similar to the effects of other classes of clinically used conventional volatile anesthetics such as enflurane (Joksovic et al., 2005a) and isoflurane (Ries and Puil, 1999). Hence, different classes of general anesthetics may have a common inhibitory effect on thalamocortical information transfer, which critically depends on the activity of T-channels. Our data further support the potential importance of T-channels as cellular targets for general anesthesia.

In at least two reports, potent inhibition of native T-currents by 1-octanol has been demonstrated. This was based on the findings that 1 μM 1-octanol blocked 75% of T-current in neonatal dorsal root ganglion cells (Scott et al., 1990), and 20 μM 1-octanol completely blocked T-currents in inferior olivary neurons (Llinás 1988). However, full-concentration response curves were not generated, and the underlying mechanism of this potent inhibition of T-currents by 1-octanol was not further investigated in these studies.

Our study with recombinant T-channel isoforms expressed in HEK 293 cells indicates that these isoforms are inhibited by 1-octanol at concentrations up to 30-fold less potent than T-currents in native nRT cells. Binding of some drugs to inactivated states of the channel is an important property because it can provide pharmacological selectivity to their action. In particular, this mechanism can stabilize channel in inactive states and thus decrease availability of channel at physiological membrane potentials. We explore this hypothesis and found that 1-octanol significantly decreased availability of channel as evidenced by a hyperpolarizing shift of approximately 10 mV in steady-state inactivation curves of both recombinant CaV3.3 (Fig. 3) and native nRT T-currents (Fig. 4). Although this is an important mechanism contributing to the preferential reduction of peak T-current at depolarized membrane potentials, it is unlikely that this could account for a large difference in potency in native versus recombinant T-currents.

One possible reason for discrepancy in potency of T-current inhibition by 1-octanol between the native and recombinant cells could be different contents of membrane lipids. For example, it has been shown that membrane composition of lipid bilayers can drastically affect ability of anesthetics such as halothane and propofol (Hemmings and Adamo, 1994), as well as 1-octanol (Shen et al., 1999), to interact with lipid-bound regulatory domains of PKC. Furthermore, in our study, the potent inhibitory effect of 1-octanol on T-current in nRT cells was critically dependent on constitutive Ca\(^{2+}\)-dependent PKC, as shown by the fact that it was abolished with agents to inhibit it, as do the Ca\(^{2+}\) ion chelator BAPTA and Go 6976, a specific inhibitor of Ca\(^{2+}\)-dependent isoforms of PKC. We also found that PMA induced a small but significant up-regulation of baseline T-current in nRT cells. Furthermore, Go 6976 blocked baseline T-current, strongly suggesting that endogenous PKC in nRT cells modulates T-current. In contrast, Go 6976 at the same concentration did not significantly affect recombinant CaV3.3 currents. In addition, changing intracellular Ca\(^{2+}\) buffering capacity with low concentrations of EGTA did not increase potency of 1-octanol in inhibiting recombinant CaV3.3 currents in HEK 293 cells. Thus, baseline T-current activity seems to be differently regulated in native and recombinant cells. This is important, indicating a novel form of T-current modulation in nRT neurons by PKC. Earlier, we reported that nRT T-currents, LTS, and burst firing can be directly modulated by other endogenous agents, such as reducing amino acid \(\gamma\)-cysteine (Joksovic al., 2006) and S-nitrosothiols (Joksovic et al., 2007). Thus, different regulatory mechanisms regulate the expression of T-current in the finely tuned neuronal excitability of these cells.

The molecular basis for PKC modulation of T-current in nRT cells remains unknown. Several isoforms of PKC in neurons can be Ca\(^{2+}\)-dependent (e.g., \(\alpha\), \(\beta\), \(\beta\III\), \(\gamma\)), or Ca\(^{2+}\)-independent (e.g., \(\delta\), \(\varepsilon\), \(\eta\), \(\theta\), \(\mu\)) (Rebecchi and Pentyala, 2002). In situ hybridization studies have shown that PKC isoforms...
can be differentially expressed in the central nervous system, including the thalamus (Minami et al., 2000). Our results strongly suggest that Ca\(^{2+}\)-dependent PKC isoforms are tonically active in the up-regulation of T-current in nRT neurons and can be potently inhibited by 1-octanol. Recent studies with recombinant T-channel isoforms expressed in Xenopus laevis oocytes (Park et al., 2006) and mammalian cells (Chemin et al., 2007) indicate that the amplitude of currents of all three known isoforms, Ca\(_{\text{a3.2}}\), Ca\(_{\text{a3.2}}\), and Ca\(_{\text{a3.3}}\), may be enhanced up to 3- to 4-fold by PKC activation with prolonged incubation with PMA. Park et al. (2006) further showed that critical sites located in the I-II loop of the channel are responsible for the interaction of PMA and Ca\(_{\text{a3.1}}\). However, the exact amino acid residues targeted by PKC action, presumably phosphorylation, have not been identified yet. It is interesting that the stimulatory effects of PKC upon T-current amplitude were strictly temperature-dependent in study using mammalian cells (Chemin et al., 2007), whereas similar effects were observed in oocytes at room temperature (Park et al., 2006). It is noteworthy that different T-current isoforms in two adjacent nuclei of the thalamus seem to be differentially regulated by PKC. For example, PMA inhibits T-current in thalamocortical cells of ventrobasal nucleus that express predominantly Ca\(_{\text{a3.1}}\) channels (Cheong et al., 2008) but enhances T-current in nRT cells that express Ca\(_{\text{a3.2}}\) and Ca\(_{\text{a3.3}}\) channels (this study). Extensive molecular studies in both recombinant and native cells are needed to decipher the precise mechanisms of the molecular interaction between T-channels, PKC, and anesthetic alcohols.

In conclusion, we have demonstrated that 1-octanol potently inhibits native T-currents in nRT neurons, probably by modulating Ca\(^{2+}\)-dependent PKC signaling. Moreover, T-channels in nRT neurons have a key function in thalamocortical oscillations, which in turn regulate physiological processes, such as level of arousal and sleep, awareness, and sensory information transfer, as well as pathological processes such as absence seizures (Steriade, 2005). Thus, PKC modulation in nRT cells by anesthetic alcohols may contribute to the sedative, hypnotic, and anticonvulsant effects of general anesthesia.

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References


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