Differential expression of intrinsic membrane currents in defined cell types of the anterolateral bed nucleus of the stria terminalis

Sayamwong E. Hammack, Irakli Mania, Donald G. Rainnie

AFFILIATION: Emory University
Department of Psychiatry and Behavioral Science
Center for Behavioral Neuroscience

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CORRESPONDING AUTHOR:
Donald G. Rainnie
Emory University
Department of Psychiatry and Behavioral Science
Center for Behavioral Neuroscience
Yerkes Neuroscience Building
954 Gatewood Road
Atlanta, GA 30329

Phone: 404-712-9714
FAX: 404-712-9645
Email: drainni@emory.edu
Abstract

The anterolateral group of the bed nucleus of the stria terminalis (BNST_ALG) plays a critical role in a diverse array of behaviors; however, little is known of the physiological properties of neurons in this region. Using whole-cell patch clamp recordings from rat BNST_ALG slices in vitro, we describe three distinct physiological cell types. Type I neurons were characterized by the presence of a depolarizing sag in response to hyperpolarizing current injection that resembled activation of the hyperpolarization-activated cation current \( I_h \), and a regular firing pattern in response to depolarizing current injection. Type II neurons exhibited the same depolarizing sag in response to hyperpolarizing current injection, but burst-fired in response to depolarizing current injection, which was indicative of the activation of the low threshold calcium current \( I_T \). Type III neurons did not exhibit a depolarizing sag in response to hyperpolarizing current injection, and instead exhibited a fast time-independent rectification that became more pronounced with increased amplitude of hyperpolarizing current injection, and was indicative of activation of the inwardly rectifying potassium current \( I_{K(\text{IR})} \). Type III neurons also exhibited a regular firing pattern in response to depolarizing current. Using voltage-clamp analysis we further characterized the primary active currents that shaped the physiological properties of these distinct cell types, including \( I_h \), \( I_T \), \( I_{K(\text{IR})} \), the voltage-dependent potassium current \( I_A \), and the persistent sodium current \( I_{NaP} \). The functional relevance of each cell type is discussed in relation to prior anatomical studies, as well as how these currents may interact to modulate neuronal activity within the BNST_ALG.

Keywords: Extended Amygdala, Electrophysiology, Anxiety
Intrinsic currents defining cell types in the BNST

Introduction

A growing body of evidence suggests that the modulation of neural activity in the bed nucleus of the stria terminalis (BNST) plays a critical role in the expression of a diverse array of behaviors, such as anxiety-like behavior (Walker et al. 2003), learned helplessness (Hammack et al. 2004), drug reinforcement (for review, see (Aston-Jones and Harris 2004)), drug reinstatement behavior (Erb and Stewart 1999), conditioned defeat (Jasnow et al. 2004), and circadian rhythmicity (Amir et al. 2004). This diversity suggests an underlying BNST neurocircuitry that might be equally varied.

Indeed, the BNST is a complex structure that can be grossly divided into an anterior and a posterior subdivision by the fibers of the stria terminalis (De Olmos et al. 1985; Ju et al. 1989), as well as into dorsal and ventral subdivisions by the fibers of the anterior commissure (De Olmos et al. 1985; Ju et al. 1989). However, as many as 30 individual subdivisions have been identified in the BNST based on their cytoarchitecture, chemoarchitecture and connectivity (Dong et al. 2001; Ju et al. 1989), suggesting that functional specificity may also be ascribed to different subregions within the BNST. Consistent with this hypothesis, more medial BNST subregions form an integral part of the medial extended amygdala, and are believed to mediate the expression of defense and reproductive behaviors (see (Newman 1999) for review). In contrast, the more lateral BNST subdivisions form part of the central extended amygdala (Alheid and Heimer 1988), and mediate the expression of behaviors associated with affect (Walker et al. 2003).

Excitability of the central extended amygdala is tightly regulated by afferent projections arising from the basolateral nucleus of the amygdala (BLA) (Adamec 1989; Casada and Dafny 1992; Dalsass and Siegel 1987; Dong et al. 2001) and, not surprisingly,
BLA lesions block many of the same affective behaviors thought to be mediated by activation of the central extended amygdala (Walker and Davis 1997). Significantly, afferent projections from the BLA primarily target neurons in a region of the lateral BNST that Swanson and colleagues (2001) have termed the anterolateral group (BNST\textsubscript{ALG}, (Dong et al. 2001)), suggesting that the activation of this region may contribute to the expression of affective behavior, such as those elicited by stressful stimuli. Consistent with this hypothesis, electrical stimulation of the BLA \textit{in vivo} mimics the increased activation of BNST\textsubscript{ALG} neurons that is normally observed in response to stressful stimuli (Adamec 1989; Casada and Dafny 1992; Dalsass and Siegel 1987). Similarly, stimulation of the BNST\textsubscript{ALG} mimics many of the endocrine, cardiovascular, and respiratory responses that are elicited by stressful stimuli (Casada and Dafny 1991). Hence, the BNST\textsubscript{ALG} may represent a critical node in the neural circuitry that functions to coordinate an appropriate affective response to stressful stimuli.

However, the BNST\textsubscript{ALG} is not a homogeneous structure and is comprised of the anterolateral, subcommissural, oval, juxtacapsular, fusiform and rhomboid nuclei (Dong et al. 2001). Moreover, while the majority (70-90%) of BNST\textsubscript{ALG} neurons can be classified as medium-sized spiny GABAergic neurons (McDonald 1983; Sun and Cassell 1993), at least three different subtypes have been identified based on either their somatic morphology (Larriva-Sahd 2006; McDonald 1983), their co-expression of peptide neurotransmitters, or their receptor pharmacology (Arluison et al. 1994; Gray and Magnuson 1992; Woodhams et al. 1983). Not surprisingly, therefore, BNST\textsubscript{ALG} neurons also exhibit a heterogeneous response to local neurotransmitter release. Hence, extracellular single-unit recording studies have shown that BNST\textsubscript{ALG} neurons can be either excited and/or inhibited by opiates
Intrinsic currents defining cell types in the BNST\textsubscript{ALG} (Casada and Dafny 1993; Dalsass and Siegel 1990), norepinephrine (Casada and Dafny 1993), acetylcholine (Casada and Dafny 1993), and oxytocin (Ingram et al. 1990). Hence, even within discrete BNST\textsubscript{ALG} nuclei stressful stimuli may activate different categories of BNST\textsubscript{ALG} neurons.

More recently, we and others have shown that the response of individual BNST\textsubscript{ALG} neurons to neurotransmitters such as 5-HT or NE depends on two inter-related factors: 1) their postsynaptic receptor expression profile, and 2) their intrinsic membrane properties (Egli and Winder 2003; Levita et al. 2004; Rainnie 1999). Indeed, these initial current-clamp studies suggested that multiple, physiologically distinct, cell types exist within subdivisions of the BNST\textsubscript{ALG} (Egli and Winder 2003; Rainnie 1999).

Here, we extend our initial current clamp observations and describe three distinct physiological cell types within the BNST\textsubscript{ALG}. Furthermore, using voltage-clamp analysis we have characterized the primary active currents that play a major role in shaping the physiological properties of these distinct cell types.

**Methods**

*Slice Preparation*

Prior to slice preparation, 24-48 day old male Sprague Dawley rats, were housed four per cage and had ad libetum access to food and water. Care was taken to minimize the number of animals used, and all procedures were done in accordance with policy guidelines set by the National Institutes of Health, and were approved by the Emory University Institutional Animal Care and Use Committee. To obtain BNST\textsubscript{ALG} slices, rats were decapitated under isoflurane anesthesia (Abbott Laboratories, North Chicago, IL), and the brains rapidly removed and placed in ice-cold kynurenic acid-based artificial cerebrospinal
Intrinsic currents defining cell types in the BNST\textsubscript{ALG} fluid (ACSF\textsubscript{KA}), which contained (in mM): NaCl (130), KCl (3.5), KH\textsubscript{2}PO\textsubscript{4} (1.1), MgCl\textsubscript{2} (6.0), CaCl\textsubscript{2} (1.0), NaHCO\textsubscript{3} (30), glucose (10), and kynurenic acid (2). The glutamatergic antagonist, kynurenic acid, was included in the ACSF\textsubscript{KA} in order to suppress any unwanted effects of glutamate release that may occur during tissue slicing. Divalent cation levels were also adjusted to reduce the probability of neurotransmitter release. A block of tissue containing the BNST was then mounted on the chuck of a Leica VTS-1000 vibrating microtome (Leica Microsystems Inc., Bannockburn, IL), and 350 µm coronal slices were cut. Slices were then hemisected and hand-trimmed to remove excess tissue lateral to the BNST\textsubscript{ALG}. Slices were transferred to a holding chamber containing ACSF\textsubscript{KA} at room temperature and gassed with a 95%-5% oxygen/carbon dioxide mixture for one hour before being placed in oxygenated control ACSF containing (in mM): NaCl (130), KCl (3.5), KH\textsubscript{2}PO\textsubscript{4} (1.1), MgCl\textsubscript{2} (1.3), CaCl\textsubscript{2} (2.5), NaHCO\textsubscript{3} (30), and glucose (10). Experiments started a minimum of ½ an hour following the transfer of slices into the control ACSF.

Visual Identification of BNST\textsubscript{ALG} Neurons

Slices were placed in a Warner Series 20 recording chamber (Warner Instruments, Hamden, CT) mounted on the fixed stage of a Leica DM-LFS microscope (Leica Microsystems). Slices were fully submerged and continuously perfused at a rate of 1-2 ml/min with heated (32°C) and oxygenated ACSF. Neurons were visualized using infrared (IR) illumination and a 40X water immersion objective (Leica Microsystems). Images were captured using an IR sensitive charge-coupled device (CCD) digital camera (Orca ER, Hamamatsu, Tokyo Japan) coupled to a Meteor-II video frame grabber (Matrox Electronic
Systems Ltd, Dorval, Canada), and displayed on a computer monitor using Simple PCI 611 software (Compix Inc., Cranberry Township, PA).

**Recording Procedures**

For whole-cell patch-clamp recording, thin walled borosilicate glass patch electrodes (WPI, Sarasota, FL) were pulled on a Flaming/Brown micropipette puller (Model P-97, Sutter Instruments). Patch electrodes had resistances ranging from 4-8 MΩ, when filled with a standard patch solution that contained (in mM): K-Gluconate (138), KCl (2), MgCl₂ (3), phosphocreatine (5), K-ATP (2), NaGTP (0.2), HEPES (10). The patch recording solution was adjusted to a pH of 7.3 with KOH and had a final osmolarity of 280 mOsm. Whole-cell patch clamp recordings were obtained as previously described (Levita et al. 2004; Rainnie et al. 2004), using an Axopatch-1D amplifier (Molecular Devices, Sunnyvale, CA), a Digidata 1320A A-D interface, and pClamp 8.2 software (Molecular Devices). In cell attached-mode, patch electrode seal resistance was considered acceptable if it was >1.5 GΩ. For all experiments, whole cell patch-clamp configuration was initially established in current-clamp mode. Neurons were excluded from analysis if they showed a resting membrane potential (Vm) more positive than –55 mV, and/or had an action potential that did not overshoot +5 mV. Subsequent data from current- and voltage-clamp recordings were sampled at rates determined by the speed of the measured response. In general, current clamp data were filtered at 5 kHz, and voltage clamp data at 2 kHz. Access resistance for voltage clamp protocols was monitored over the course of each experiment, and was considered acceptable if it was < 20 MΩ. Long duration effects of drug application were recorded on a chart recorder (Kipp & Zonen, Bohemia, NY).
Drug Application

Drugs were applied by gravity perfusion at the required concentration in the circulating ACSF. Drugs used included: cesium chloride (CsCl) 5 mM; nickel chloride (NiCl₂) 500 µM; 4-aminopyridine (4-AP) 1-10 mM; barium chloride (BaCl₂) 500 µM; bicuculline methiodide 30 µM; verapamil hydrochloride 100 µM; riluzole 30 µM; tetrodotoxin (TTX) 1 µM, and tetraethylammonium chloride (TEA-Cl) 20 mM from Sigma-Aldrich (Saint Louis, MO); and 3-[[3,4-Dichlorophenyl)methyl]amino]propyl] diethoxymethyl)phosphinic acid (CGP 52432) 1 µM; (RS)-3-(2-Carboxypiperazin-4-yl)-propyl-1-phosphonic acid ((RS)CPP) 10 µM; 6,7-Dinitroquinoxaline-2,3-dione (DNQX) 20 µM; and 4-(N-ethyl-N-phenylamino)-1,2-dimethyl-6-(methylamino) pyridinium chloride (ZD 7228) 30-60 µM, purchased from Tocris (Ellisville, MO). All drugs were stored frozen as concentrated stock solutions in dH₂O except DNQX, which was made in 50% dimethyl sulfoxide, and buffered to pH 7.3.

Statistics

Statistical analyses are described for each experiment in the following sections. All statistics were performed using GraphPad Prism version 4.02, (GraphPad Software, Inc., San Diego, CA).

Current Clamp Characterization of the Basic Electrophysiological Properties of BNSTₐₗ₉ Neurons

A standardized series of current clamp test protocols were conducted to determine the physiological characteristics of each neuron at a holding potential of –60 mV, unless otherwise stated. Hence, the passive and active membrane properties of each neuron were
Intrinsic currents defining cell types in the BNST$_{ALG}$ primarily assessed by determining the voltage response to transient (750 ms), incremental current steps ranging from -75 pA to +25 pA. The membrane input resistance ($R_m$) was determined from the peak voltage response to a -5 pA current injection. The properties of single action potentials were determined using short duration 10 ms, high amplitude (15-115 pA), incremental current injections. Based on the readout of these protocols, neurons were assigned to one of three groups, Types I - III (see figure 2). Statistical comparisons between these groups were made using one-way ANOVA for each of the following variables: $V_m$; $R_m$; time constant for membrane charging ($\tau$); action-potential threshold, amplitude, rise- and decay time, and half width. A post-hoc Tukey’s Multiple Comparison Test (Tukey’s MCT) was conducted to determine individual group differences.

**Voltage Clamp Characterization of the Intrinsic Membrane Currents of BNST$_{ALG}$ Neurons**

The characteristic voltage response of Type I – III BNST$_{ALG}$ neurons suggested that several cell type-specific intrinsic membrane currents may be expressed by these neurons. The following voltage-clamp experiments were conducted to more fully characterize these currents.

1. **Hyperpolarization-Activated Non Selective Cation Current ($I_h$)**

Type I and II neurons showed a time-dependent depolarizing sag in the voltage response to hyperpolarizing current injection (see Figure 2), which was reminiscent of that mediated by activation of the hyperpolarization-activated non-selective cation current ($I_h$) in other regions of the CNS (for review, see (Roberts and Seigelbaum 2003)). To isolate and characterize the properties of $I_h$-like currents, the ACSF was supplemented with 1 µM
Intrinsic currents defining cell types in the BNST_{ALG}

tetrodotoxin (TTX) and 500 μM NiCl\textsubscript{2} to block sodium- and low threshold T-type calcium currents, respectively. The voltage-dependency of I\textsubscript{h} activation was determined using a dual step protocol (McCormick and Pape 1990). Here, steady-state I\textsubscript{h} activation was determined by applying a conditioning step command to potentials ranging from –100 to –45 mV for 1.5 s. The membrane potential was then stepped to -85 mV, as illustrated in Figure 4, and the peak of the resulting “tail” current measured, normalized to a percent of the maximum tail current response, and plotted as a function of the voltage achieved during the conditioning step. The normalized steady-state activation curve was then fit with a Boltzmann equation of the form:

\[ I = \frac{1}{1 + \exp\left((V-V_{50})/k\right)} \] (Equation 1)

Where, \( I \) = the normalized current, \( V_{50} \) = half maximal membrane potential, and \( k \) describes the slope. The inclusion of either CsCl (5 mM) or ZD7228 (30 μM) in the ACSF blocked the tail current. The significance of drug effect was determined using an F-test to compare the control activation curves with those obtained in the presence of the I\textsubscript{h} channel blockers.

To compare I\textsubscript{h} activation kinetics across cell types, we determined the time constant of I\textsubscript{h} activation (\( \tau_{h} \)) in response to a standardized transient (600 ms) voltage step from –60 to –100 mV, where \( \tau_{h} \) was determined as the time taken to reach 1/e of the steady-state current calculated using a single-exponential best-fit subroutine of the Clampfit software (Molecular Devices). A frequency histogram of the \( \tau_{h} \) value for each neuron was constructed and the distribution was best fit by the sum of two Gaussian curves of the form:

\[ Y = \text{amplitude}*\exp(-0.5((X-mean)/SD)^2) \] (Equation 2)
Where, amplitude = the peak response, exp = the base of the natural logarithm, mean = the average time constant, and SD = the standard deviation of the distribution.

2. Low Threshold Calcium Current (\(I_T\))

To isolate and characterize the properties of \(I_T\), the stock ACSF was adjusted to the following composition (in mM): NaCl (120), KCl (3.5), HEPES (10), TEA-Cl (20), MgCl\(_2\) (1.3), CaCl\(_2\) (2.5), 4-AP (1.0), CsCl (5.0), TTX (0.001), NaHCO\(_3\) (30), and glucose (10). TEA-Cl and 4-AP were included to suppress depolarization-activated outward potassium currents (see below), and CsCl was included to suppress \(I_h\). A dual-step protocol was employed to examine the current-voltage relationship of \(I_T\) activation. Here, the membrane potential was stepped to \(-90\) mV for 500 ms, and then stepped to command potentials ranging from \(-60\) to \(-40\) in increments of 5 mV, for 500 ms. Peak inward currents were normalized to the maximum evoked current (\(I_T/\text{\(I_{T(max)}\)}\)), and plotted as a function of the command voltage. Steady-state leak currents were subtracted from the raw data using the leak-subtraction subroutine of the Clampfit software. Data were then fit with a Boltzman equation (equation 1). Leak current was assumed to be linear and was corrected using the following equation:

\[
\text{Corrected current} = \frac{\text{original current} - \text{stimulus waveform}}{0.001 \times R_m}
\]  

(Equation 3)

The time constant of \(I_T\) decay (\(\tau_T\); deactivation) was determined by fitting a single exponential to the decay phase of the peak \(I_T\) current using the best fit subroutines of the Clampfit software. \(\tau_T\) was determined as the time taken to reach \(1/e\) of the peak current.

\(I_T\) channels inactivate close to the resting membrane potential of many neurons, and require a period of membrane hyperpolarization to de-inactivate prior to activation (see
Intrinsic currents defining cell types in the BNST_{ALG} (Perez-Reyes 2003)). To examine the de-inactivation kinetics of I_T, the membrane potential was stepped from –60 to -100 mV for 500 ms in 10 mV increments, and then stepped to a command potential of –50 mV for 500 ms. Peak I_T amplitude was normalized to I_T(max) and plotted as a function of the conditioning voltage. Leak currents were subtracted from the raw data (see above), and data was fit with a Boltzman equation (equation 1), and the half-maximal activation voltage determined.

To examine the temporal kinetics of I_T de-inactivation (τ_{deinact}) and inactivation (τ_{inact}) we employed two additional dual-step protocols. Here, τ_{deinact} was determined by varying the duration of the conditioning prepulse from 100 ms to 1 s, in 100 ms increments, and plotting the peak I_T amplitude evoked by a command step to –50 mV as a function of the prepulse duration. Leak-corrected currents were normalized to the maximum current, and data were fit with a single exponential association equation:

\[ I = I_{max} \times (1 - e^{-K \times t}) \text{ (Equation 4)} \]

Where, I = the normalized current, t = time, I_{max} = the maximum current attained (near 1), and K = the rate constant. To determine τ_{inact}, the time between a fixed amplitude (-100 mV) conditioning prepulse and the command step (-50 mV) was increased from 15 ms to 555 ms in 60 ms increments. Peak currents were corrected for leak, normalized to the maximum evoked current, and plotted as a function of the interval between the conditioning and the activation steps. Data were fitted with a single exponential decay equation:

\[ I = I_{max} \times e^{-K \times t} + I_{sst} \text{ (Equation 5)} \]

Where, I = the normalized current, t = time, I_{max} = the peak current, I_{sst} = the steady-state current, and K = the rate constant.
3. Transient Outward Potassium Conductance ($I_A$)

Our initial $I_T$ studies suggested that this current was tightly regulated by a transient outward current, which had activation kinetics and a voltage-dependency similar to that reported for the transient outward potassium current, $I_A$. In order to isolate and further characterize this current, the ACSF was adjusted to the following composition (in mM): NaCl (110), KCl (3.5), TEA-Cl (20), KH$_2$PO$_4$ (1.1), MgCl$_2$ (3.3), CaCl$_2$ (0.5), CdCl$_2$ (0.15), NiCl$_2$ (0.5), TTX (0.001), verapamil (0.1), NaHCO$_3$ (30), ZD7228 (0.06), and glucose (10). Here, TEA-Cl was included to block both outwardly rectifying- and some calcium-dependent potassium currents. A cocktail of CdCl$_2$, verapamil, and NiCl$_2$ was included to maximally block calcium currents. Unless otherwise noted, all $I_A$ voltage clamp protocols were conducted from a holding potential of –40 mV.

To examine the voltage-dependency of $I_A$ activation and de-inactivation dual step protocols similar to those outlined above for $I_T$ were employed. As for $I_T$ analyses, $I_A$ current responses were leak corrected, normalized to the maximum current response, and plotted as a function of the command voltage. Data was fit with a Boltzman equation (Equation 1). The time constant of $I_A$ decay ($\tau_A$) was determined by fitting an exponential curve to the decay phase of the $I_A$ current, $\tau_A$ was determined as the time taken to reach 1/e of the steady-state current. $I_A$ decay was best-fit using the dual exponential subroutine of the Clampfit software (Molecular Devices). In order to determine whether the rate of $I_A$ decay was voltage-dependent, $\tau_A$ was plotted as a function of command voltage and a regression coefficient calculated for each time constant.
The de-inactivation time constant ($\tau_{\text{deinact}}$) for $I_A$ was determined using a dual step protocol similar to that used for $I_T$. Here the duration of the conditioning prepulse was increased from 50 ms to 700 ms in 50 ms increments, followed by a 500 ms command step to $-25$ mV. To improve the temporal resolution of this protocol (see inset of figure 7) shorter (10 ms) increments were used such that the duration of the conditioning prepulse varied from 10 to 110 ms. Similar to $I_T$, the inactivation time constant ($\tau_{\text{inact}}$) was determined using a protocol in which the interval between the prepulse and the command step increased from 0 to 900 ms in increments of 100 ms. Analyses were conducted on the peak outward current elicited at the beginning of each command step. Current responses were corrected for leak, and normalized to the maximum current response and plotted as a function of the duration between the first and second steps. Data were fitted with a one-phase exponential decay equation (Equation 5).

4. Inwardly Rectifying Potassium Current

A characteristic of Type III neurons was that they exhibit a time-independent depolarizing rectification in the voltage response to hyperpolarizing current injection of increasing amplitude (see Figure 2). This rapid anomalous rectification was reminiscent of that produced following activation of members of the family of inwardly rectifying potassium channels ($K_{IR}$, see Nichols and Lopatin 1997). The current underlying the anomalous rectification was examined in voltage clamp mode using a standard hyperpolarization protocol in which the voltage command was stepped from $-60$ mV to $-100$ mV for 600 ms in 10 mV increments.

5. Persistent Sodium Current ($I_{NaP}$)
In some BNST\textsubscript{ALG} neurons, the kinetics of decay for the voltage response to transient (10 ms) depolarizing current injection far outlasted that predicted by the $\tau_m$ of these neurons. The long duration and voltage-sensitivity of the potential decay were similar to that previously reported following activation of the non-inactivating voltage-dependent sodium current, $I_{\text{NaP}}$ (also called the persistent sodium current). To determine whether BNST\textsubscript{ALG} neurons express $I_{\text{NaP}}$, the ACSF was adjusted to the following composition (in mM): NaCl (34), KCl (5), MgCl\textsubscript{2} (3), CaCl\textsubscript{2} (2), BaCl\textsubscript{2} (2), TEA-Cl (80), 4-AP (4), CsCl (3), CdCl\textsubscript{2} (0.2), glucose (10), and NaHCO\textsubscript{3} (30). In addition, the patch pipette solution was modified to one that contained (in mM): CsMeSO\textsubscript{4} (120), TEA (3), MgCl\textsubscript{2} (1), HEPES (10), phosphocreatinine (10), K-ATP (2), and Na-GTP (0.2). Using these two solutions in combination allowed us to block most of the intrinsic currents outlined above, in order to isolate $I_{\text{NaP}}$. The sodium concentration was reduced to 34 mM and replaced by TEA-Cl to prevent action potential generation. The voltage dependence of $I_{\text{NaP}}$ was examined using a voltage ramp protocol (Urbani and Belluzzi 2000) in which the command voltage was ramped from $-100$ mV to $+10$ mV at a rate of 10 mV/s. $I_{\text{NaP}}$ was observed as a transient inward current activating at approximately $-46$ mV.

**Results**

*Cell Types of the BNST\textsubscript{ALG}*

In the course of our ongoing studies of the pharmacological (Levita et al. 2004) and physiological (Rainnie 1999) properties of BNST\textsubscript{ALG} neurons, we have recorded from over 276 neurons. For these studies all recordings were made from neurons located in the lateral BNST\textsubscript{ALG} dorsal to the anterior commissure, which is comprised of the anterolateral area
Intrinsic currents defining cell types in the BNST\textsubscript{ALG} proper, the oval nucleus, rhomboid nucleus, and the juxtacapsular nucleus of the BNST\textsubscript{ALG} as defined by Dong and Swanson (2004). For each BNST\textsubscript{ALG} neuron included in these studies, we routinely conducted a series of standardized current clamp protocols (see Methods) to determine their characteristic voltage response to transient depolarizing and hyperpolarizing current injection. Based on several characteristic voltage trajectories, BNST\textsubscript{ALG} neurons could be categorized into three distinct cell types (Type I – III). Hence, neurons were categorized according to the presence or absence of: 1) a time-dependent depolarizing sag in the voltage response to hyperpolarizing current injection, which exhibited a rebound depolarization upon termination of the current pulse (Figure 2B, Type I and II); 2) an enhanced rebound depolarization upon termination of the hyperpolarizing current steps, which exceeded that previously described, and which was often of sufficient magnitude to trigger action potentials (Figure 2B, Type II); 3) a time-independent depolarizing rectification of the voltage response to hyperpolarizing current injection, which did not exhibit any rebound depolarization upon termination of the current injection (Figure 2B, Type III); and 4) their action potential firing pattern triggered in response to transient depolarizing current injection (Figure 2A).

**Type I Neurons**

Type I neurons accounted for 29% of all recorded BNST\textsubscript{ALG} neurons, had a resting membrane potential (V\text{m}) of $-60.0 \pm 0.6$ mV, and a mean input resistance (R\text{m}) of $452.6 \pm 30.0$ M\text{\(\Omega\)}. As shown in Table 1, a significant difference was observed in both the R\text{m} (F(2,226) = 16.02, p < 0.05), and V\text{m} (F(2,275) = 3.6, p < 0.05) across the three cell types. In contrast, no significant difference was seen for the $\tau$ (F(2,59) = 0.44, p > 0.05). For both
V_m and R_m, Tukey's MCT revealed that Type I neurons differed significantly from Type III neurons, but not from Type II neurons.

In response to transient (750 ms) hyperpolarizing current injection, Type I neurons exhibited a characteristic depolarizing sag (rectification) in their voltage response that was both time- and voltage-dependent, such that the amplitude and rate of onset of the rectification increased with increasing membrane hyperpolarization (see Figure 2B, Type I). The input resistance measured at the peak of the hyperpolarizing voltage response was always greater than that determined once the rectification had reached a steady state level, suggesting that the sag was mediated by a voltage-dependent increase in membrane conductance. Type I neurons also exhibited a transient depolarizing rebound potential on termination of the hyperpolarizing current injection, the amplitude and rate of onset of which also increased with increasing levels of initial membrane hyperpolarization. Significantly, the amplitude and rate of onset of the rebound depolarization mirrored the level of the depolarizing rectification observed in the voltage response during hyperpolarizing current injection, suggesting that they were mechanistically connected. Similar properties have been previously reported in neurons from multiple brain regions following activation of the hyperpolarization-activated non-selective cation current, I_h (for review see Roberts and Seigelbaum, 2003). By comparison, the voltage response to transient depolarizing current injection was relatively linear until the threshold for action potential generation was reached.

In response to supra-threshold depolarizing current injection, Type I neurons exhibited a regular firing pattern, such that the first inter-spike-interval (ISI, 110.8 ± 8.7
ms) did not significantly differ ($t = 0.01, p < 0.05, n = 40$) from the last ISI (154.5 ± 11.9 ms). On average, single action potentials had a threshold for activation of -43.2 ± 0.5 mV, an amplitude of 75.7 ± 3.9 mV, a 10-90% rise time of 0.44 ± 0.02 ms, a 90-10% decay time of 0.88 ± 0.05 ms, and a half-width of 0.95 ± 0.04 ms. These properties are summarized in Table 1, and compared with those of Type II and III neurons. As illustrated in Table 1, spike properties did not significantly differ between cell types.

**Type II Neurons**

Type II neurons were the most abundant of BNST<sub>ALG</sub> neurons, accounting for 55% of all recorded cells. These neurons had a V<sub>m</sub> of –58.0 ± 0.5 mV, and an R<sub>m</sub> of 377.4 ± 15.7 MΩ. Type II neurons also exhibited a depolarizing sag in response to hyperpolarizing current injection that was similar to that described for Type I neurons. However, in contrast to Type I neurons, the amplitude and rate of onset of the rebound depolarization observed at the termination of the hyperpolarizing current injection was always much larger than the degree of depolarizing rectification observed. Significantly, the amplitude of the rebound depolarization often surpassed action potential threshold and triggered a rebound burst of action potentials (see figure 2B, Type II), suggesting that Type II neurons express additional active currents that could be modulated by prior membrane hyperpolarization.

Unlike Type I neurons, the response of Type II neurons to transient depolarizing current injection was nonlinear. Hence, in Type II neurons subthreshold depolarizing current injection evoked a depolarizing “hump” that peaked within 150 ms of the onset of current injection and which became more pronounced at membrane potentials at, or near, threshold for action potential firing. Expression of this transient depolarizing potential
caused Type II neurons to exhibit a burst-firing pattern, which was characterized by a rapid succession of action potentials followed by a delay before the onset of the next spike or succession of spikes (Figure 2A, Type II). Winder and coworkers (2003) reported a similar transient depolarizing potential in ventral BNST neurons that was blocked by NiCl₂ (200 μM), a concentration that preferentially blocks the low-threshold calcium current, Iₜ (Egli and Winder 2003), suggesting that Type II neurons of the BNST_ALG might also express the Iₜ current.

Following the initial burst of action potentials, Type II neurons either fire in a regular pattern (Figure 2A, Type II), fire in bursts, or stop firing all together (accommodate). The variability of this second response is likely due to differential expression of outward rectifying currents and calcium-dependent potassium currents, and/or differences in the properties of the calcium currents that generate the initial burst. These differences suggest that even within Type II neurons there is heterogeneity in their physiological responses. Unlike the net action potential firing pattern, the properties of single spikes evoked in Type II neurons did not differ significantly from those described for Type I or Type III neurons (see Table 1).

**Type III Neurons**

**Type III** neurons made up 16% of recorded BNST_ALG neurons, had a Vm of −64 ± 1.1 mV, and an Rm of 357.8 ± 38.1 MΩ. Unlike Type I and II neurons, Type III neurons did not show a prominent time-dependent depolarizing sag in response to hyperpolarizing current injection. Instead, Type III neurons exhibited a fast time-independent rectification that became more pronounced with increased amplitude of current injection (Figure 2B,
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Type III). Unlike the time-dependent rectification observed in Type I and II neurons, no rebound depolarization was observed in Type III neurons on the termination of the hyperpolarizing current injection. These properties are similar to those previously reported in other brain regions following activation of an inwardly-rectifying potassium current, $K_{\text{IR}}$ (De Jeu et al. 2002; Nisenbaum and Wilson 1995), which suggested that Type III neurons may preferentially express this current.

In response to depolarizing current injection, Type III neurons fired with a regular firing pattern; like Type I neurons the first ISI ($65.8 \pm 8.2$ ms) did not significantly differ ($t = 0.07, p < 0.05, n = 40$) from the last ISI ($82.1 \pm 9.3$ ms). However, Type III neurons showed a significantly longer latency to first spike onset ($F(2,59) = 29.21, p < 0.05$) than Type I and II neurons (data not shown).

**Intrinsic Membrane Currents of BNST\textsubscript{ALG} Neurons**

Having categorized BNST\textsubscript{ALG} neurons into three physiologically distinct subtypes based on our current clamp data, we next recorded neurons in voltage clamp mode to isolate and characterize some of the intrinsic membrane currents that act to shape the voltage response of these neurons. Below we present the biophysical properties of the five most prominent membrane currents expressed by one or more subtype of BNST\textsubscript{ALG} neuron. It should be noted that these data are not presented in any particular order of importance.

1. **Expression of the Non-Selective Cation Current ($I_h$)**

   Approximately 84% of BNST neurons display a time-dependent rectification of the voltage response to hyperpolarizing current injection (Figure 3B; see also (Egli and Winder 2003; Rainnie 1999)). Because the rectification was similar in many ways to that...
Intrinsic currents defining cell types in the BNST\textsubscript{ALG} previously reported as being mediated by activation of I\textsubscript{h} channels, we first examined the response of BNST\textsubscript{ALG} neurons to addition of the non-specific I\textsubscript{h} channel blocker CsCl (5 mM, n = 13) to the ACSF. In current clamp, application of CsCl completely blocked the depolarizing sag (not shown), increased Rm by 161.6 ± 12.2\%, and caused a -4.2 ± 1.8 mV hyperpolarizing shift in resting membrane potential, suggesting that the majority of BNST\textsubscript{ALG} neurons actively express I\textsubscript{h} channels, and that tonic activation of I\textsubscript{h} channels plays a significant role in regulating both the Vm and the Rm of these neurons.

In voltage clamp, the depolarizing sag was associated with the activation of a time- and voltage-dependent inward current. The time constant for current activation (\(\tau\_h\)), measured as the time taken for the current to reach 1/e of the maximal steady-state level in response to a voltage step from –60 to –80 mV, ranged from 47.7 to 254.1 ms. The population distribution of \(\tau\_h\) is illustrated in Figure 3A. As can be seen, \(\tau\_h\) exhibited a bimodal distribution that was best fit with a biphasic Gaussian equation rather than a single Gaussian (F(1,22) = 9.7, p < 0.05). These data suggested that those BNST\textsubscript{ALG} neurons expressing I\textsubscript{h} could be further differentiated into “fast” and “slow” \(\tau\_h\) neurons based on their I\textsubscript{h} kinetics. The mean \(\tau\_h\) value for the “fast” I\textsubscript{h} subgroup was 110 ± 2.1 ms, and for the “slow” I\textsubscript{h} subgroup was 173 ± 2.5 ms.

In agreement with observations of I\textsubscript{h} kinetics elsewhere in the brain (Morris et al. 2004; Roberts and Greene 2005), the rate of activation of the I\textsubscript{h}-like current increased as the command potential became more negative (Figure 3D). Hence, transient hyperpolarizing step commands to -70 mV from a holding potential of -60 mV evoked an I\textsubscript{h}-like current with a time constant of activation \(\tau\_h\) = 160.6 ± 17.8mS, whereas steps commands to -100
Intrinsic currents defining cell types in the BNST\textsubscript{ALG} mV evoked an I\textsubscript{h}-like current with significantly faster kinetics, $\tau_h = 88.4 \pm 4.4$ ms ($t = 3.98$, $p < 0.05$, $n = 78$)

In order to examine the kinetics of the I\textsubscript{h}-like current in greater detail; we employed a dual-step voltage clamp protocol and a modified ASCF that blocked concurrent activation of unwanted currents (see Methods). A typical example of an intrinsic I\textsubscript{h}-like “tail” current in a BNST\textsubscript{ALG} neuron is illustrated in Figure 4B (insert). As reported previously (Morris et al. 2004), the amplitude of the I\textsubscript{h}-like tail current was dependent on the voltage attained during the conditioning prepulse, and showed a maximal amplitude of $-96.8 \pm 9.7$ pA with prepulse steps to -120 mV. Fitting the data with a Boltzman equation revealed a half maximal activation voltage, $V_{1/2} = -80.13 \pm 0.5$ mV ($n = 6$), and a slope factor of $-11.7 \pm 0.5$ mV (Figure 4C). Inclusion of CsCl (5 mM) in the modified ACSF fully blocked the I\textsubscript{h}-like “tail” current (Figure 4B inset). Moreover, application of the specific I\textsubscript{h} channel blocker, ZD 7228 (30 $\mu$M), caused a time-dependent attenuation of the “tail” current ($F(3,114) = 49.8$, $p < 0.05$, data not shown), further suggesting that this was indeed mediated by activation of I\textsubscript{h} channels.

2. Expression of the T-type Calcium Current ($I_T$)

Type II neurons were identified primarily by their tendency to burst fire in response to depolarizing current injection, and at the offset of hyperpolarizing current injection (Figure 2B, Type II). Consistent with earlier reports (Egli and Winder 2003), addition of NiCl\textsubscript{2} (500 $\mu$M, $n = 9$) to the extracellular ACSF fully blocked burst firing in Type II neurons (data not shown), suggesting that burst-firing in these neurons may be mediated by activation of the low-threshold calcium current, $I_T$. 
Intrinsic currents defining cell types in the BNST\textsubscript{ALG}

To further investigate if BNST\textsubscript{ALG} neurons express an \(I_T\)-like current we employed a dual-step voltage clamp protocol (Figure 5A) in association with a modified ACSF to isolate intrinsic calcium currents (see Methods). Typically, \(I_T\) calcium channels require a period of membrane hyperpolarization to de-inactivate before they can be activated by subsequent membrane depolarization (for review see (Perez-Reyes 2003)). Consequently, we investigated the activation properties of the \(I_T\)-like current using a transient (500 ms) hyperpolarizing prepulse to -90 mV, to increase the probability of \(I_T\) channel de-inactivation, followed by a series of depolarizing step commands of increasing amplitude. A typical example of the series of transient, inward, \(I_T\)-like currents generated in response to the dual-step protocol is illustrated in Figure 5A. As expected, the dual-step protocol evoked a series of transient inward currents that increased in amplitude with increasing depolarizing step commands, and which reached a peak amplitude of \(-102.0 \pm 25.1\) pA with step commands to -45 mV (\(n = 6\)). Moreover, the rate of rise of the \(I_T\)-like current increased significantly with increasing depolarizing step commands (\(t = 3.81, p < 0.05, n = 13\)), such that the time to peak with steps to -50 mV was 34.1 ± 3.2 ms, compared to 21.3 ± 2.3 ms for steps to -35. In contrast, the rate of decay of the \(I_T\)-like current was relatively constant with a time constant for decay, \(\tau_T = 19.9\) ms, irrespective of the voltage achieved (\(n = 4\)). We next examined the voltage-dependency of \(I_T\) activation. As illustrated in Figure 5A, the \(I_T\)-like current activated from membrane potentials close to -60 mV, had a half maximal activation potential (\(V_{1/2}\)) of \(-50.0 \pm 0.5\) mV, and a slope factor of \(2.4 \pm 0.8\) mV (\(n = 5\)).
To examine the voltage-dependency of de-inactivation we used a similar dual-step protocol, except here the amplitude of the hyperpolarizing prepulse was varied and the amplitude of the subsequent depolarizing step command remained constant. As before, the peak inward current evoked during the depolarizing step command was normalized to the maximal evoked inward current and plotted as a function of membrane potential (see Figure 5B). Here, the amplitude of the normalized peak inward current increased as a function of the amplitude of the hyperpolarizing step command, and showed a half maximal voltage for de-inactivation ($V_{1/2}$) of $-77.6 \pm 0.6$ mV, and a slope factor of $-4.0 \pm 0.6$ mV ($n = 7$) when fit with a Boltzman equation.

Significantly, the $I_T$-like inward current was completely blocked following addition of 500 $\mu$M NiCl$_2$ to the ACSF (Figure 5A, inset; $n = 5$), and significantly attenuated by addition of the $I_T$ channel blocker, mibefradil (10 $\mu$M; $F(1, 85) = 44.7$, $p < 0.05$, data not shown), suggesting that the transient inward current observed in BNST$_{ALG}$ neurons was indeed mediated by the opening of low-threshold T-type calcium channels.

We next examined the temporal kinetics of de-inactivation and inactivation of the $I_T$ current in BNST$_{ALG}$ neurons. We reasoned that the time constant of de-inactivation ($\tau_{deinact}$) would give a first approximation of the time required for an inhibitory postsynaptic event to significantly increase the probability of $I_T$ channel opening in BNST$_{ALG}$ neurons on subsequent depolarization. Here, $\tau_{deinact}$ was determined by varying the duration of a hyperpolarizing prepulse, which preceded a depolarizing step command of fixed amplitude (Figure 6A). The normalized $I_T$ current was then plotted as a function of the duration of the preceding hyperpolarizing prepulse. As expected, the $I_T$ amplitude increased with
Intrinsic currents defining cell types in the BNST$_{ALG}$

increasing prepulse duration, and showed an e-fold increase ($\tau_{\text{deinact}}$) with a prepulse duration of 208.0 mS ($n = 5$; see Figure 6A). Hence, in BNST$_{ALG}$ neurons inhibitory synaptic events of $\sim 200$ ms duration could significantly facilitate any subsequent excitatory synaptic input by de-inactivating $I_T$ channels.

However, excitatory synaptic input onto BNST neurons fluctuates stochastically and would not always occur immediately after an inhibitory synaptic input. Consequently, we next examined the temporal domain in which an inhibitory synaptic input may continue to influence (facilitate) subsequent excitatory inputs ($\tau_{\text{inact}}$). Here, the interval between the offset of the hyperpolarizing prepulse and the onset of the depolarization step command was incrementally increased (see Figure 6B). The normalized $I_T$ current was then plotted as a function of the interval duration. As illustrated, $I_T$ amplitude decreased with increasing duration of the interpulse interval and showed an e-fold decrease in amplitude, $\tau_{\text{inact}}$, of 56.1 ms ($n = 5$, see Figure 6B). Hence, the temporal kinetics of $I_T$ channels in Type II neurons may function as a “memory” of the preceding inhibitory event, thereby defining a time window during which any subsequent excitatory synaptic input may be facilitated.

3. Expression of the Transient Voltage-Dependent Potassium Current ($I_A$)

In response to depolarizing current injection at, or near, threshold for action potential generation most Type III neurons showed a marked delay in the time to onset of the first spike (see Figure 2A). Similar delays in action potential firing have been reported in neurons from diverse regions of the CNS as resulting, in part, from activation of the rapidly inactivating outward potassium current, $I_A$ (Burdakov and Ashcroft 2002; Varga et al. 2004).
Consequently, we next examined the relative expression of $I_A$-like currents in BNST$_{ALG}$ neurons. Surprisingly, an $I_A$-like current was observed in all of the neurons examined ($n = 19$), and was not restricted to the 16% of neurons that might be expected if it was only expressed by Type III neurons.

Like $I_T$ channels, $I_A$ channels require a period of membrane hyperpolarization to remove channel inactivation before they can activate. Consequently, to examine the expression of $I_A$-like currents in BNST$_{ALG}$ neurons we used dual step protocols similar to those used to isolate $I_T$ (outlined above). Because $I_A$ channels are reported to de-inactivate at more depolarized potentials than $I_T$ (Burdakov and Ashcroft 2002; Varga et al. 2004) we minimized any potential contamination by $I_T$ by conducting these studies at a holding potential of $-40$ mV, since at this potential $I_T$ channels are thought to be fully inactivated. In addition, these experiments were conducted using a modified ACSF supplemented with ZD7228 (60 $\mu$M), and NiCl$_2$ (500 $\mu$M), to block $I_h$ and $I_T$, respectively.

We first examined the activation properties of $I_A$-like currents in BNST$_{ALG}$ neurons using a transient (500 ms) hyperpolarizing prepulse to $-100$ mV followed by depolarizing step commands of increasing amplitude (Figure 7A). In all neurons examined, this protocol elicited a transient outward current that peaked within $\sim 20$ ms of the onset of the depolarizing step command, and which rapidly decreased in amplitude thereafter. When the resultant series of outward currents were normalized and fit with a Boltzman equation, the $I_A$-like current was seen to activate at membrane potentials significantly more depolarized than that observed for $I_T$ ($\sim -40$ mV), have a half maximal activation potential ($V_{1/2}$) of $-3.1 \pm 2.7$ mV, and a slope factor of $10.1 \pm 0.96$ mV ($n = 10$). Significantly, the $I_A$-like current
was markedly suppressed by addition of 4-aminopyridine (4-AP; 5 mM) to the ACSF (F(4, 102) = 338.8, p < 0.05), suggesting that the transient outward current was indeed mediated by activation of $I_A$ channels (Figure 7A, inset).

Similar to the $I_T$ current, the rate of rise of the $I_A$ current increased with increasing depolarizing step commands, such that the time to peak current was $17.1 \pm 2.3$ ms for depolarization steps to –30 mV, and $8.1 \pm 0.8$ ms for depolarization steps to +5 mV. This voltage dependency is consistent with previous reports of $I_A$ currents in other regions (Locke and Nerbonne 1997).

At a holding potential of –40 mV, the decay phase of the $I_A$ current was best fit by a second-order exponential equation with two significantly different rates of decay ($t = 11.0, p < 0.05$), suggesting that $I_A$ channels in BNST$_{ALG}$ neurons might be heteromers of different $I_A$ channel subunits. The fast decay had a time constant for deactivation ($t_A$) of $21.4 \pm 1.2$ ms ($n = 7$), and a slow decay time constant (slow $t_A$) of $183.5 \pm 16.1$ ms ($n = 7$). Interestingly, the fast $t_A$ was voltage-sensitive, whereby fast $t_A$ decreased from $22.2 \pm 5.5$ ms with steps to –35 mV, to $14.8 \pm 3.3$ ms with steps to +5 mV. In contrast, the slow $t_A$ appeared to be voltage-independent such that with steps to –35 mV the slow $t_A$ was $187.0 \pm 28.6$ ms, and to +5 mV the slow $t_A$ was $178.8 \pm 58.3$ ms.

We next investigated the voltage-dependence of $I_A$ de-inactivation using a dual-step protocol similar to that outlined above for the de-inactivation of $I_T$ (Figure 7B). As expected, the amplitude of the $I_A$ current increased with increasing levels of prepulse hyperpolarization (Figure 7B). A plot of the normalized $I_A$ current amplitude as a function of the prepulse potential was fit with a Boltzmann equation and revealed that $I_A$ channels in
BNST\textsubscript{ALG} neurons were half-maximally de-inactivated \((V_{1/2})\) at \(-70.4 \pm 2.4\) mV \((n = 4)\), with a slope factor of \(-10.8 \pm 2.6\) mV.

We next examined if the de-inactivation and inactivation kinetics of the \(I_A\) current showed similar temporal profile to that of \(I_T\) using protocols similar to those outlined above. As illustrated in Figure 8A, \(I_A\) amplitude increased with increasing duration of the hyperpolarizing prepulse, and showed an e-fold (2.13) increase \((\tau_{\text{deinact}})\) with hyperpolarizing steps of 34.6 ms \((n = 10)\). We then determined the temporal domain for the inactivation kinetics \((\tau_{\text{inact}})\) of \(I_A\). Here the interval between the hyperpolarizing prepulse and the depolarizing step command was incrementally increased and the resultant \(I_A\) current normalized and plotted as a function of the interval duration. As illustrated in Figure 8B, \(I_A\) showed an e-fold decrement in amplitude with a \(\tau_{\text{inact}}\) of 211.41 ms \((n = 4)\). In BNST\textsubscript{ALG} neurons de-inactivation of \(I_A\) channels occurs approximately 7 times faster than deactivation, and hence in Type I & III neurons, which do not express \(I_T\), the response to inhibitory synaptic input would tend to be enhanced.

4. Expression of the Inwardly Rectifying Potassium Current \((I_{K(IR)})\)

As illustrated in Figure 2B, Type III neurons show a rapid and dramatic decrease in the voltage excursion evoked by transient hyperpolarizing current injection of increasing amplitude. This voltage-dependent, and time-independent, decrease in input resistance was similar to the fast rectification reported in other brain regions that is mediated by activation of an inwardly rectifying potassium current, \(I_{K(IR)}\) (De Jeu et al. 2002; Nisenbaum and Wilson 1995). Activation of \(I_{K(IR)}\) channels is thought to play a pivotal role in the maintenance of the resting membrane potential, as well as regulating action potential
Intrinsic currents defining cell types in the BNST\textsubscript{ALG} duration (for review see (Nichols and Lopatin, 1997)). Significantly, both the fast anomalous rectification (Figure 9A), and the underlying increase in membrane conductance observed in BNST\textsubscript{ALG} neurons (Figure 9B) were blocked by addition of the non-selective K\textsubscript{IR} blocker, barium chloride (BaCl\textsubscript{2}, 500\textmu M), to the ASCF. At a holding potential of -60 mV, application of BaCl\textsubscript{2} elicited a 6.9 ± 1.1 mV (n = 22) depolarizing shift in the membrane potential of BNST\textsubscript{ALG} neurons that was associated with a 138 ± 5.0 % increase in Rm (from 425.2 ± 41.2 M\Omega to 557.3 ± 49.9 M\Omega), and a 133.6 ± 9.5% increase in $\tau_m$. In voltage clamp, the depolarization was seen to be mediated by a 16.6 ± 5.4 pA (n = 9) inward current, and had a reversal potential of -74.2 ± 2.0 mV. Hence, I\textsubscript{K(IR)} channels appear to play a significant role in regulating the resting membrane potential of Type III neurons. It is noteworthy, that in several Type III neurons, blockade of I\textsubscript{K(IR)} channels with BaCl\textsubscript{2} unmasked a small, time-dependent, inward current indicative of the presence of I\textsubscript{h} (see Figure 9A).

5. Expression of the Persistent Sodium Current ($I_{NaP}$)

While examining the properties of single action potentials in BNST\textsubscript{ALG} neurons it was noted that transient (10 ms), subthreshold, depolarizing current injection could elicit a voltage response whose decay far outlasted the normal time constant for membrane discharge. Similar slow depolarizing potentials have been observed in neurons of the entorhinal cortex and hippocampus (Saraga and Skinner 2002), where they were attributed to the activation of a slowly inactivating persistent sodium current ($I_{NaP}$). Consequently, we next examined BNST\textsubscript{ALG} neurons for the presence of the persistent sodium current ($I_{NaP}$). These experiments were conducted using a modified ACSF that contained potassium and...
Intrinsic currents defining cell types in the BNST\textsubscript{ALG}

calcium channel blockers, as well as a reduced sodium concentration to prevent contamination by all-or-none action potentials (see Methods). The presence of \textit{I\textsubscript{NaP}} was probed using a voltage ramp protocol in which the command voltage was ramped from –100 mV to +10 mV at a rate of 10 mV/s. In all BNST\textsubscript{ALG} neurons tested (n = 14), the slow voltage ramp protocol elicited a robust inward current (Figure 9C) that activated at membrane potentials more positive than -50 mV, reached a peak at \(-27.5 \pm 2.2 \text{ mV}\), and had a half maximal activation potential of \((V_{1/2})\) of \(-39.4 \pm 1.8 \text{ mV}\). In all cases the inward current was completely blocked by the sodium channel blocker, TTX (1 \(\mu\text{M}, n = 6\), Figure 9C), and was significantly attenuated (74\%) by addition of the non-selective \textit{I\textsubscript{NaP}} channel blocker, riluzole (30 \(\mu\text{M}\), to the ACSF (t = 5.93, p < 0.05, data not shown). These data suggest that like \textit{I\textsubscript{A}} channels, \textit{I\textsubscript{NaP}} channels are ubiquitously expressed in BNST\textsubscript{ALG} neurons.

Discussion

\textit{Identification of distinct physiological cell types within the BNST\textsubscript{ALG}}

Previous studies in the BNST\textsubscript{ALG} have suggested the existence of distinct neuronal subpopulations that differ in their cytoarchitecture, chemoarchitecture, and projection patterns. Here, we provide additional evidence for three physiologically distinct subpopulations of BNST\textsubscript{ALG} neurons that can be categorized according to their response to hyperpolarizing and depolarizing current injection. Furthermore, we extend these observations to show that the differential expression of at least five intrinsic membrane currents shapes the response of each cell type and, hence, dictate their input-output relationship.
In our initial study on the properties of cells in the medial and lateral BNST (Rainnie 1999), we reported that neurons in these two regions could be differentiated by their relative expression of a depolarizing sag in the voltage response to hyperpolarizing current injection, which was thought to be mediated by the hyperpolarization-activated cation conductance, $I_h$, as well as a transient depolarizing potential that was thought to be mediated by the low threshold calcium current, $I_T$. These observations were subsequently confirmed in mice in a more detailed study by Egli and Winder (2003), who further reported that some BNST neurons also exhibit a fast inward rectification in the voltage response to hyperpolarizing current injection (Egli and Winder 2003). However, these were predominantly current clamp studies and hence the underlying intrinsic membrane currents were not characterized beyond establishing their presence in BNST neurons. Consequently, it was unclear if BNST neurons exhibit varying levels of the same intrinsic currents or if distinct physiological subtypes of neurons exist within the BNST.

Here, we used a simple visual discrimination of the current clamp traces recorded from 276 BNST$_{ALG}$ neurons to provisionally divide this cell population into three distinct physiological cell types. The criteria used for the discrimination were based solely on the shape of the voltage response to hyperpolarizing and depolarizing current injection (see Figure 2A and B). Hence, Type I neurons expressed a depolarizing sag in response to hyperpolarizing current injection, but did not exhibit any signs of low-threshold spiking or burst-firing activity. Type II neurons expressed the depolarizing sag, and also exhibited robust rebound spiking and/or burst firing activity. Type III neurons exhibited a pronounced fast inward rectification to hyperpolarizing current injection, and did not exhibit any signs of low-threshold spiking or burst-firing activity. Interestingly, a similar
Intrinsic currents defining cell types in the BNST\textsubscript{ALG} distribution of BNST neurons expressing these characteristics has been reported in mice (Egli and Winder 2003), suggesting that these three physiological cell types are not species specific.

Based on the criteria outlined above, we reasoned that the three subtypes of BNST\textsubscript{ALG} neuron would differentially express one or more of at least three intrinsic membrane currents, \textit{I}_h, \textit{I}_T, and \textit{I}_K(\text{IR}). Neurons of the central nucleus of the amygdala (CeA), a GABAergic homologue of the BNST\textsubscript{ALG} (for review see (Alheid 2003)), have also been subdivided into at least three cell types based primarily on their action potential firing patterns (Martina et al. 1999). Significantly, the firing pattern of each subtype was differentially modulated by application of the \textit{I}_A-channel blocker, 4-AP, or the \textit{I}_T-channel blocker, NiCl\textsubscript{2}, suggesting that distinct subtypes of neurons in this BNST homologue can also be differentiated based on their expression of intrinsic membrane currents.

Outlined below is a discussion of the properties for each of the intrinsic currents expressed by BNST\textsubscript{ALG} neurons, followed by a brief discussion of how these currents work in concert to shape the characteristic response profiles of the different BNST\textsubscript{ALG} cell types, and the potential significance of physiological diversity.

\textit{Hyperpolarization-activated non-specific cation current, \textit{I}_h}

The hyperpolarization-activated cyclic nucleotide gated current, \textit{I}_h, is a mixed cation current that activates at membrane potentials more negative than -50 mV, has a half-maximal activation voltage (\textit{V}_{1/2}) that ranges between -60 to -90 mV, and is blocked by external application of either CsCl, or ZD7288 (for review see (Robinson and Siegelbaum 2003)). BNST\textsubscript{ALG} neurons exhibited a voltage- and time-dependent inward current with similar physiological and pharmacological properties such that the inward current
deinactivated at potentials below -50 mV (Figure 4C), had a $V_{1/2}$ of $\sim -80$ mV, and was blocked by both 5 mM CsCl and 30 µM ZD7288. Significantly, pharmacological blockade of $I_h$ channels in BNST$_{ALG}$ neurons resulted in a net hyperpolarizing shift in the resting membrane potential ($\sim -60$ mV to -64.2 mV), which was associated with a significant increase in the membrane input resistance (161.6%). Hence, in Type I and II BNST$_{ALG}$ neurons, $I_h$ plays a significant role in regulating both the resting membrane potential and the resting membrane input resistance.

Four genes (HCN1-4) encode distinct isoforms of the $I_h$ channel. The BNST has high expression levels of HCN1 mRNA, moderate levels of HCN3, and low levels of HCN2 and 4 mRNA (Monteggia et al. 2000). Importantly, each of these isoforms differ in their kinetics, voltage dependency, and sensitivity to cAMP modulation (for review see Robinson and Siegelbaum 2003). Thus, HCN3 channels activate more slowly than HCN2 channels, which in turn activate slower than HCN1 channels (Altomare et al. 2003; Mistrik et al. 2005). Moreover, HCN isoforms have been shown to co-assemble into functional heteromers, and form $I_h$ channels with properties that are often intermediate between their constituent homomers (Chen et al. 2001).

BNST$_{ALG}$ neurons could be subdivided into two populations with either slow, or fast, $I_h$ activation kinetics, which may reflect differences in the subunit composition of the $I_h$ channels in Type I and II BNST$_{ALG}$ neurons. The mean activation rate of the faster group (110 ms) is similar to the activation kinetics reported for homomeric HCN1 channels (Santoro et al. 2000), whereas the mean rate for the slower group (173 ms) suggested the presence of heteromeric $I_h$ channels that may contain HCN1 subunits in association with one or more subunits of HCN2-4. Evidence from in situ hybridization studies (ibid) would
suggest that heteromeric channels of the slower group would be comprised of HCN1 and HCN3 subunits. Consistent with this hypothesis, using single cell RT-PCR analysis of the mRNA from recorded BNST_{ALG} neurons we have found neurons that contain mRNA only for HCN1, or both HCN1 and HCN3, and rarely HCN2 or HCN4 (Hammack et al. 2006). Moreover, \(I_h\) channels formed from heteromers of HCN1/HCN4 have much slower activation kinetics (>5 s; (Altomare et al. 2003)) than those observed in BNST_{ALG} neurons and, hence, are unlikely to mediate \(I_h\) currents in the BNST_{ALG}.

Significantly, the different HCN isoforms also differ in the degree to which they can be modulated by cAMP. For example, cAMP has minimal effect on HCN1 channel activity (Santoro et al. 1998), strongly augments HCN2 channel activity (Ludwig et al. 1998), and inhibits HCN3 channel activity (Mistrik et al. 2005). We have shown that BNST_{ALG} neurons can be subdivided into two distinct groups based on their fast versus slow \(I_h\) activation kinetics. The different \(I_h\) kinetics most likely reflect differences in the channel subunit composition, and hence cAMP may differentially modulate \(I_h\) activity in these two cell populations. Consequently, any receptor-effector complex that activates the cAMP second messenger cascade would be expected to differentially regulate the excitability of BNST_{ALG} neurons. In the CNS, \(I_h\) channel activity is enhanced by serotonin (Cardenas et al. 1999), dopamine (Wu and Hablitz 2005), as well as corticotropin-releasing factor (CRF, (Qiu et al. 2005)), all of which are released into the BNST_{ALG} during exposure to a stressor or novel environments. Hence, local release of neurotransmitters in response to stressors, novelty, drugs of abuse, or goal-directed behaviors might promote \(I_h\)-mediated activity in select subtypes of BNST_{ALG} neurons.

*Low-threshold calcium current, \(I_T\)*
In our first BNST paper ((Rainnie 1999); see also (Egli and Winder 2003)), we suggested that neurons in the lateral BNST express a low-threshold $I_T$-like calcium current. However, this study did not examine either the properties of the $I_T$-like current, or its relative distribution across cell types. Here, we expand on these original observations to show that an $I_T$ current does in fact mediate burst-firing activity in the BNST$_{ALG}$, but only in Type II neurons.

Hence, Type II neurons showed a transient inward current that decayed rapidly ($\tau = 20$ ms), had $V_{1/2}$ of activation of $-50$ mV, a $V_{1/2}$ of deinactivation of $-77.6$ mV, and had a mean amplitude of $-102$ pA in response to step commands from -90 mV to -40 mV. These properties are consistent with those previously reported for $I_T$ in several other brain regions (see (Perez-Reyes 2003)). Moreover, the transient inward current was significantly attenuated by the relatively selective T-type calcium channel blockers, NiCl$_2$ (500 µM), and mibefradil (10 µM).

Calcium channels are complex proteins composed of four or five distinct subunits in which the $\alpha 1$ subunit contains the pore-forming core (see (Catterall 2000) for review). To date a family of at least 10 subunit genes have been identified and cloned. Three $\alpha$-subunits that form calcium channels with properties similar to $I_T$ have been cloned and named $\alpha 1G$, $\alpha 1H$, and $\alpha 1I$ (Perez-Reyes 2003). Of these three subunits, in situ hybridization studies have shown moderate to high levels for $\alpha 1G$ and $\alpha 1H$ mRNA in the BNST$_{ALG}$ (Talley et al. 1999). Whereas, the voltage dependence of these three $\alpha$-subunits are similar, they have significantly different kinetics and sensitivity to blockers (Lee et al. 1999). Hence, $I_T$ channels incorporating the $\alpha 1I$ subunit have slower inactivation (137 ms) kinetics than
Intrinsic currents defining cell types in the BNST\textsubscript{ALG}

those containing \(\alpha1G\) or \(\alpha1H\) (Klockner et al. 1999). Consistent with the \textit{in situ} hybridization studies (ibid), the relatively rapid inactivation kinetics reported here for I\(_T\) in BNST\textsubscript{ALG} neurons suggests that these channels may incorporate either the \(\alpha1G\) and/or \(\alpha1H\) subunits. Although, \(\alpha1G\) subunits are 24-fold less sensitive than \(\alpha1H\) sensitivities to blockade by NiCl\(_2\) (Lee et al. 1999), the concentration used in the present study (500 \(\mu\)M) could not differentiate the subunit composition of I\(_T\) in BNST\textsubscript{ALG} neurons.

Several neurotransmitters have been shown to modulate I\(_T\) channel function including 5-HT (Fraser and MacVicar 1991), acetylcholine (Fisher and Johnston 1990), substance P (Ryu and Randic 1990), estrogen (Qiu et al. 2006), catecholamines (Marchetti et al. 1986) and angiotensin II (Buisson et al. 1992). All of these neurotransmitters are released in the BNST, and hence might regulate I\(_T\) functioning in Type II neurons. Intriguingly, 5-HT has been shown to inhibit I\(_T\) via 5-HT\(_2\) receptor activation (Placantonakis et al. 2000), while 5-HT\(_7\) receptor activation has been reported to increase I\(_T\) (Lenglet et al. 2002). Both 5-HT\(_2\) and 5-HT\(_7\) receptors are functionally expressed in BNST\textsubscript{ALG} neurons (Hammack et al. 2005), and it remains to be determined if activation of either of these two receptors subtypes can modulate I\(_T\) in Type II neurons.

\textit{Voltage-dependent potassium current, I\(_A\)}

Significantly, all three subtypes of BNST\textsubscript{ALG} neuron expressed an I\(_A\)-like current. Consistent with the description of I\(_A\) elsewhere in the brain, the I\(_A\) current in BNST\textsubscript{ALG} neurons exhibited marked voltage-dependency and had a \(V_{1/2}\) of activation of \(-3.1\) mV, a \(V_{1/2}\) of deinactivation of \(-70\) mV, and a mean current of 612 pA following voltage steps from \(-100\) mV to 0 mV (for review see (Rudy 1988)). However, while the threshold for
activation (> -40 mV) was similar to that reported in several brain regions (see (Burdakov and Ashcroft 2002), it was more positive than that in others (Locke and Nerbonne 1997).

Native $I_A$ channels are made up of the gene products of several members of the Kv potassium channel family; namely Kv1.4, Kv 3.3, Kv3.4, and the Kv4 family of subunits. Importantly, each Kv subunit has distinct activation and inactivation kinetics as well as differential sensitivity to pharmacological blockers (see (Robertson 1997) for review). Three of these subunits, Kv1.4, Kv4.2, and Kv4.3 have been detected in the BNST$_{ALG}$ (Serodio and Rudy 1998). It is noteworthy, that the activation and deinactivation properties of Kv4.3 are similar to the values reported here for $I_A$ in BNST$_{ALG}$ neurons (Tsaur et al. 1997), suggesting that these neurons may express a common Kv channel subunit. Consistent with this hypothesis, the inactivation decay of $I_A$ was best fit by a dual-exponential having both a fast ($\tau = 21$ ms) and a slow time constant ($\tau = 184$ ms), and a similar biexponential function has been reported elsewhere for Kv4.3 subunits (Franqueza et al. 1999). Intriguingly, Kv 4.1 and 4.2 are thought to be localized to the somatodendritic compartment (Song 2002), and are blocked by high extracellular 4-AP (5 mM), much like the $I_A$ current observed in BNST$_{ALG}$ neurons. In contrast, Kv1.4 subunits are localized to the axonal compartment and sensitive to low µM concentrations of 4-AP (for review see (Gutman et al. 2005)). Hence, members of the Kv4 family of subunits may regulate somatic excitability of BNST$_{ALG}$ neurons, whereas channels containing the Kv1.4 subunit may modulate dendritic excitability.

As discussed below, in Type II BNST$_{ALG}$ neurons $I_A$ acts to attenuate $I_T$ and, hence, regulate burst-firing activity in these neurons. Like $I_T$, several neurotransmitters have been shown to modulate $I_A$ channel function including 5-HT (Farley and Auerbach 1986),
acetylcholine (Nakajima et al. 1986), norepinephrine (Aghajanian 1985), and cholecystokinin (Burdakov and Ashcroft 2002). Significantly, many of the same neurotransmitters that can increase \( I_T \) (i.e. 5-HT and acetylcholine) also act to inhibit \( I_A \). As discussed below, such a combination of effects would dramatically enhance burst-firing in Type II BNST\sub{ALG} neurons.

**Inwardly-rectifying potassium current, \( I_{K(IR)} \)**

In current clamp mode, many BNST\sub{ALG} neurons expressed a type of fast anomalous rectification that was most apparent in Type III neurons (see Figure 2). In voltage clamp, the fast anomalous rectification was associated with a voltage-dependent increase in membrane conductance that was blocked by addition of 500 \( \mu \text{M} \) BaCl\textsubscript{2} to the ACSF, consistent with it being mediated by activation of an inwardly-rectifying potassium current, \( I_{K(IR)} \).

Seven subfamilies of \( I_{K(IR)} \) channel have been cloned (\( K_{ir1-7} \)) (Dascal et al. 1993; Ho et al. 1993), which can be distinguished based on their rectification properties and their regulation by intracellular messengers (for review see (Stanfield et al. 1994)). \( K_{ir} \) channels are tetramers with a unique two transmembrane domain structure (see (Nichols and Lopatin 1997)). Significantly, members of the \( K_{ir} \) 2.0 subfamily are constitutively active, blocked by barium, and found predominantly in the brain, where these channels are thought to play a major role in clamping the resting membrane potential close to the reversal potential for potassium (Nichols and Lopatin 1997). These data are consistent with the observation that Type III neurons have a lower resting membrane potential compared to Type I and Type II neurons (see Table 1). Moreover, \( K_{ir}2.3 \) channels are reported to localize in the dendrites...
Intrinsic currents defining cell types in the BNST\textsubscript{ALG} (Day et al. 2005) and postsynaptic membranes of cortical pyramidal neurons (Inanobe et al. 2002), where they are thought to regulate excitatory transmission (Takigawa and Alzheimer 2002). Hence, in Type III BNST	extsubscript{ALG} neurons I\textsubscript{K(IR)} channels may also function to regulate excitatory afferent input.

However, BaCl\textsubscript{2} induced a membrane depolarization and increased the input resistance of all neurons tested (data not shown), suggesting that I\textsubscript{K(IR)} channels are ubiquitously expressed in BNST\textsubscript{ALG} neurons but that the relative number and/or subunit composition varies from cell type to cell type. Hence, subpopulations of BNST\textsubscript{ALG} neurons may express unique combinations of Kir subunits. Consistent with this hypothesis, using RT-PCR we have detected mRNA for Kir2.1 and 2.3 subunits in isolated sections of the BNST ((Hammack et al. 2006) but see (Karschin et al. 1996)). Moreover, Kir2.1 - Kir2.4 subunits combine to form homo- and heteromeric tetramers with different biophysical properties, and differential subunit composition may explain the variability in I\textsubscript{K(IR)} channel properties observed in neurons both between and within different brain nuclei (see (Isomoto et al. 1997)).

It should be noted, however, that in the suprachiasmatic nucleus BaCl\textsubscript{2} induced a membrane depolarization that was attenuated by blockade of the ether-à-go-go potassium channel, eag2 (De Jeu et al. 2002). It remains to be determined what contribution, if any, eag2 channels may play in regulating the activity of BNST\textsubscript{ALG} neurons.

**Persistent sodium current, I\textsubscript{NaP}**

All BNST\textsubscript{ALG} neurons examined displayed a TTX- and riluzole-sensitive inward current that activated at subthreshold membrane potentials (-50 mV), had a half maximal activation at -39 mV, and peaked at -28 mV. These properties are similar to those of I\textsubscript{NaP}
Intrinsic currents defining cell types in the BNST\textsubscript{ALG} reported in the cortex (Maurice et al. 2001; Urbani and Belluzzi 2000), but were slightly more depolarized than reports of $I_{\text{NaP}}$ in other brain regions (Gorelova and Yang 2000).

Of the ten subfamilies of sodium channels that have been identified to date ($\text{Na}_v1.1$-$1.9$ and $\text{Na}_x$), only $\text{Na}_v1.1$, $\text{Na}_v1.2$, $\text{Na}_v1.3$, and $\text{Na}_v1.6$ are expressed at high levels in the CNS (Goldin 2001). Significantly, the expression of $\text{Nav}1.5$ is restricted to the limbic regions of the brain, including the BNST (Hartmann et al. 1999). Moreover, $\text{Na}_v1.5$ channel subunits are pharmacologically distinct from other subunits in that they are inhibited by micromolar concentrations of TTX, as opposed to nanomolar concentrations. Hence, activation of sodium channels containing the $\text{Nav}1.5$ subunit may contribute to the expression of $I_{\text{NaP}}$ in BNST\textsubscript{ALG} neurons. In cerebellar Purkinje cells, $I_{\text{NaP}}$ is thought to be mediated by the $\text{Nav}1.6$ $\alpha$-subunit (Vega-Saenz de Miera et al. 1997). However, neurons of the sensorimotor cortex show layer specific differences in the properties of $I_{\text{NaP}}$ (Aracri et al. 2006), suggesting that $I_{\text{NaP}}$ channels may show region specific subunit composition.

Non-inactivating $I_{\text{NaP}}$ currents have been observed in a variety of brain regions, where they participate in the regulation of burst firing activity (Stafstrom et al. 1985), the control of membrane excitability (Wu et al. 2005), subthreshold membrane potential oscillations (Agrawal et al. 2001), and in the amplification of EPSPs in distal dendrites (Crill 1996). Interestingly, 5-HT is reported to enhance $I_{\text{NaP}}$ currents (Carr et al. 2002) possibly via activation of 5-HT$_2$ receptors (Harvey et al. 2006). We have shown that 5-HT excites a subpopulation of BNST\textsubscript{ALG} neurons via activation of postsynaptic 5-HT$_2$ receptors (Hammack et al. 2005). It remains to be determined if an enhancement of the $I_{\text{NaP}}$ current contributes to the excitatory action of 5HT, and if this action is cell type specific.
Functional relevance of multiple physiological cell types

Although there is some discussion about the merits of neural taxonomy (Nelson 2002), categorization of discrete cell types based on their intrinsic membrane currents, as outlined here, has been successfully applied to multiple subcortical structures including the inferior colliculus (Peruzzi et al. 2000), the hypothalamic paraventricular nucleus (Boudaba et al. 1996), the lateral geniculate nucleus (Kaneda and Kaneko 1991), and the central nucleus of the amygdala (Martina et al. 1999). Moreover, while we did not present gene expression data here, our preliminary single cell RT-PCR data support the premise of distinct categories of BNST\textsubscript{ALG} neurons based on their differential expression of genes encoding selective ion channels (Hammack et al. 2006). It should be noted, however, that currents which were not examined here may also play an equal role in shaping the input-output response of the different subtypes of BNST\textsubscript{ALG} neuron. Nevertheless, in this study we have defined five elementary intrinsic membrane currents whose relative expression confers on the three BNST\textsubscript{ALG} neuron subtypes many of their functional attributes.

Hence, Type I neurons comprise 29% of all BNST\textsubscript{ALG} neurons and express $I_h$, $I_A$, $I_{NaP}$, and to a lesser extent $I_{K(IR)}$. In these cells, $I_h$ was activated at voltages close to rest and played a significant role in regulating the resting membrane potential and membrane input resistance. Moreover, activation of $I_h$ produced a rebound excitation following inhibitory voltage excursions, suggesting that this current may also contribute to intrinsic membrane oscillations in Type I BNST\textsubscript{ALG} neurons. Type I neurons also express $I_{NaP}$, which has been shown to contribute to subthreshold membrane potential oscillations in neocortical neurons (Alonso and Llinas 1989; Amitai 1994), and amplify theta frequency oscillations in subicular neurons (Wang et al. 2006).
However, Type I neurons also express $I_A$ channels, and hence the extent of any membrane oscillation would be determined by the relative interaction between $I_A$, $I_h$ and $I_{NaP}$. Expression of $I_A$ may also contribute to the regular firing pattern observed in BNST$_{ALG}$ neurons. Because the majority of these neurons are thought to be GABAergic (Sun and Cassell 1993), the regular firing pattern of Type I neurons would be expected to evoke tonic GABA release, rather than the release of peptide co-transmitters as might be expected from burst firing Type II BNST$_{ALG}$ neurons (see below).

Type II neurons comprise 55% of all BNST$_{ALG}$ neurons and most likely represent a significant proportion of BNST$_{ALG}$ output neurons. Type II neurons were distinguished from Type I neurons only by their robust expression of the $I_T$ current. Nevertheless, the addition of this single current to their repertoire had a significant impact on the functional properties of Type II neurons compared to Type I neurons. In Type II BNST$_{ALG}$ neurons, the rebound excitation following an inhibitory voltage excursion was markedly enhanced when compared to the rebound excitation observed in Type I BNST$_{ALG}$ neurons, suggesting that $I_T$ and $I_h$ would act synergistically to facilitate oscillatory burst-firing in Type II BNST$_{ALG}$ neurons. Type II neurons also expressed a prominent $I_{NaP}$, further suggesting that these neurons would show a propensity for oscillatory burst firing activity. Interestingly, $I_T$ has been shown to act in concert with $I_h$ to promote rhythmic burst-firing in thalamocortical relay neurons during slow wave sleep, and changes in the rhythmicity of these neurons have been argued to underlie sleep and vigilance (see (Llinas and Steriade 2006) for review).

Due to an overlap in their kinetics of activation and deinactivation, the expression of $I_T$ is tightly regulated by $I_A$ in Type II neurons. However, the $V_{1/2}$ for activation of $I_A$ is
more depolarized than $I_T$, and hence $I_T$ would be preferentially activated with membrane depolarization at, or near rest. Subsequent depolarization would activate $I_A$ and begin to shunt $I_T$, thus setting a temporal constraint on the duration of $I_T$-induced burst firing. Hence, any factor that could attenuate $I_A$ would be expected to dramatically enhance burst firing activity in Type II neurons. High frequency burst firing activity is thought to promote the release of peptide neurotransmitters from hippocampal GABAergic neurons (Baraban and Tallent 2004). A significant proportion of GABAergic output neurons in the BNST$_{ALG}$ co-express neuropeptides, including vasoactive intestinal polypeptide, cholecystokinin, substance P, neurotensin, CRF, and methionine-enkephalin (Woodhams et al. 1983). Consequently, the transition from tonic to burst firing activity in Type II neurons might signal a transition from GABA release to neuropeptide release in target structures of Type II BNST$_{ALG}$ neurons. Behaviorally, alternating between tonic and burst firing activity in Type II neurons may signal changes in anxiety-like states in a manner similar to that proposed for thalamocortical neurons in the behavioral state transition from sleep to wakefulness (Llinas and Steriade 2006).

Type III neurons represent 16% of the total cell population, and were distinguishable from Type I and II neurons by their prominent expression of $I_{KIR}$. Consistent with this observation, Type III neurons had a more hyperpolarized resting membrane potential and a higher threshold for firing action potential generation than did Type I and II neurons. Consequently, Type III neurons would require a stronger excitatory input to reach threshold for action potential generation than Type I and II neurons. Moreover, Type III neurons express an $I_A$ current and the more hyperpolarized resting membrane potential of these neurons ensures that the probability of $I_A$ de-inactivation at
Intrinsic currents defining cell types in the BNST<sub>ALG</sub> rest is greater than in Type I and II neurons. Hence, any excitatory input would also have to overcome $I_A$ activation before pushing the membrane potential past threshold for action potential generation. These properties are reflected in the long latency to firing displayed by Type III neurons. Although Type III neurons express $I_{NaP}$, the lack of a prominent $I_h$ or $I_T$ current in these neurons would suggest that $I_{NaP}$ most likely contributes to signal processing the dendrites of these neurons rather than contributing to oscillatory firing activity.

*Are there anatomical correlates to BNST<sub>ALG</sub> cell types?*

At present, it is unclear if the three cell types described here positively correlate with any other phenotypic feature such as projection pattern, neurotransmitter content, or morphological characteristics. Initial investigations into the morphological properties of biocytin-filled neurons have not, as yet, revealed differences that correlate with either the physiological cell type or their location within specific BNST<sub>ALG</sub> subnuclei (unpublished observation); however, a thorough analysis has yet to be completed.

Within the BNST<sub>ALG</sub>, neurons showing the highest level of GABAergic immunoreactivity are thought to be intrinsic interneurons, although they also project to more distant regions of the central extended amygdala (Sun and Cassell 1993). However, GABAergic neurons of the BNST<sub>ALG</sub> also project rostrally to other forebrain regions and caudally to distal sites within the hindbrain. Indeed, a combined Golgi and electron microscopic study of the juxtacapsular nucleus, revealed two basic cell types, interneurons and projection neurons, with 80% of neurons described as bipolar projection neurons (Larriva-Sahd 2004), suggesting that GABAergic neurons may function as both intrinsic interneurons and projection neurons. Interestingly, within the oval nucleus of the BNST<sub>ALG</sub>, the most frequently observed morphological cell type (44%) were common
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Spiny neurons, which were characterized by short axons that were intrinsic to the oval nucleus and hence likely modulate local network activity (Larriva-Sahd 2006). Here, we report that 55% of BNST_{ALG} neurons were Type II neurons, thus raising the intriguing possibility that the majority of Type II neurons might be local-circuit intrinsic interneurons. These data also suggest that afferent input to the BNST_{ALG} might preferentially target an intrinsic network of interneurons that may serve to regulate projection neurons and hence the output of the BNST_{ALG}.

It is noteworthy that while the majority of BNST_{ALG} neurons are believed to be GABAergic (70-90%; McDonald 1983; Sun and Cassell 1993), the properties of Type III neurons most closely resemble those of neurons located in the lateral part of the ventral BNST that project to the ventral tegmental area (Dumont and Williams 2004), and are thought to be glutamatergenic (Georges and Aston-Jones 2002). Indeed neurons expressing vesicular glutamate transporter 2 (Vglut2) are found in several subregions of the BNST, including the ventro-lateral area (Hur and Zaborsky 2005). However, no Vglut2-containing neurons were observed in the BNST_{ALG} regions dorsal to the anterior commissure.

Many GABAergic neurons of the BNST_{ALG} also co-express one or more peptide neurotransmitters (Woodhams et al. 1983). Importantly, the co-expression patterns of peptides in the BNST_{ALG} can be either mutually inclusive or exclusive. For example, GABAergic BNST_{ALG} neurons can co-express CRF or methionine-enkephalin, but these peptides are never co-expressed in the same GABAergic neuron (Veinante et al. 1997). In contrast, the majority of CRF immunoreactive neurons are also immunoreactive for neurotensin (Shimada et al. 1989). As discussed above, burst-firing in BNST_{ALG} neurons would be expected to promote the release of peptide neurotransmitter rather than GABA.
Because many of the BNST\textsubscript{ALG} neurons that co-express peptide neurotransmitters with GABA have been shown to project to distal sites such as the locus coeruleus (Lechner and Valentino 1999), and central gray (Gray and Magnuson 1992), the valence of BNST\textsubscript{ALG} input to these sites could be dramatically altered depending on whether the firing pattern of the afferent BNST\textsubscript{ALG} neurons promotes the release of GABA, peptide or both. We have yet to determine whether the physiological cell types described herein correlate with any particular peptidergic phenotype. The development of transgenic mice expressing fluorescent reporter genes under the regulation of gene-specific promoters (Herbison et al. 2001) will greatly assist these studies.

Similarly, BNST\textsubscript{ALG} neurons can display complex responses to single neurotransmitters (Egli et al. 2005; Levita et al. 2004; Rainnie 1999). For example, 5-HT can elicit one of four different response patterns in individual BNST\textsubscript{ALG} neurons, including an inhibitory response, an excitatory response, a mixed inhibitory and excitatory response or no response (Levita et al. 2004; Rainnie 1999). Investigations are currently underway to determine if a correlation exists between the 5-HT response profile and individual BNST\textsubscript{ALG} cell types.

**Summary**

These data argue for the existence of three physiological cell types within the BNST\textsubscript{ALG}, whose response to hyperpolarizing and depolarizing current injection is shaped by the presence of several intrinsic membrane currents. These data provide the basic framework by which we can begin to build the network properties of the BNST\textsubscript{ALG}. As the BNST\textsubscript{ALG} is an important structure in regulating the behavioral response to affective stimuli, the functional mapping of networks that process this information is critical for the
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understanding of how this system may be altered during pathological states, including anxiety disorders and drug addiction.

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Present Address for Sayamwong E. Hammack:

University of Vermont

Department of Psychology

John Dewey Hall

2 Colchester Avenue

Burlington, VT 05405
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Figure Legend

Figure 1. The anterolateral group of the bed nucleus of the stria terminalis (BNST<sub>ALG</sub>), as defined by Dong et al. 2001, is outlined by the thicker hatched line. In the present studies, neurons were recorded from the lateral BNST<sub>ALG</sub> regions outlined in gray. Neurons were recorded from regions dorsal to the anterior commissure, including the anterolateral area proper, the oval nucleus, rhomboid nucleus, and the juxtacapsular nucleus. Abbreviations: AC: anterior commissure; AV: anteroventral area; AL: anterolateral area; BNST: bed nucleus of the stria terminalis; FU: fusiform nucleus; IC: internal capsule; JU: juxtacapsular nucleus; LSV: ventral lateral septal nucleus; OV: oval nucleus; SC: subcommissural zone.

Figure 2. Three electrophysiologically distinct cell types (I-III) are observed in the BNST<sub>ALG</sub> differ in their response to depolarizing and hyperpolarizing current injection. A) Type II neurons respond to depolarizing current injection with an initial burst of spikes followed by a more regular firing pattern, while types I and III fired with a regular firing pattern. B) Type I and II neurons exhibited a depolarizing sag in response to hyperpolarizing current injection that was accompanied by a rebound depolarization on the offset of current injection. In Type II neurons this rebound event was often accompanied by spikes. Type III neurons did not exhibit the depolarizing sag, but instead exhibited a fast anomalous rectification at more hyperpolarized potentials.

Figure 3. The depolarizing sag in the BNST<sub>ALG</sub> activated with different time constants. A) Frequency distribution of time constant values for the depolarizing sag across all BNST<sub>ALG</sub> neurons. B) Example in current clamp mode (CC) of fast and slowly activating depolarizing sags. C) Examples in voltage clamp mode (VC) of fast and slowly activating inward currents mediating the fast and slowly activating depolarizing sags. D) The time constant of the inward current mediating the depolarizing sag decreased as neurons were stepped to more hyperpolarized levels from –60 mV.
Figure 4. An I_h-like inward current mediated the depolarizing sag in BNST_ALG neurons. A) The dual step protocol used to determine current activation properties. Neurons were stepped from –100 to –45 mV and then stepped to –85 mV. Tail current analyses were conducted on the current produced at the beginning of the second step. B) An example of the current response induced by the protocol described in A. The tail current induced at the beginning of the second step is magnified in the box on the lower right. This tail current was completely blocked in 5 mM of the I_h channel blocker, CsCl (inset). C) The activation properties of the I_h-mediated inward current. The normalized tail current is plotted as a function of the voltage attained in the conditioning step, and exhibited a V_{1/2} of -80.13 ± 0.5 mV.

Figure 5. BNST_ALG neurons exhibit an inward current with properties of the low threshold calcium current, I_T. A) Upper trace, the activation curve used to elicit the low threshold calcium current, I_T. An example of the inward currents evoked at the beginning of the second step is shown in the box on the lower right. The current was completely blocked by the I_T channel blocker NiCl_2 (5 mM, inset). The activation curve revealed a V_{1/2} of -50.00 ± 0.46 mV. B) Upper trace, the dual step protocol used to determine the de-inactivation curve for the low threshold calcium current, I_T. An example of the inward currents evoked at the beginning of the second step is shown in the box on the lower right. The de-inactivation curve of the normalized response plotted as a function of the conditioning voltage revealed a V_{1/2} of -77.65 ± 0.67 mV.

Figure 6. De-inactivation and inactivation kinetics of the low threshold calcium current, I_T. A) The kinetics of de-inactivation were determined by varying the length of the conditioning step to (–100 mV) from 100 ms to 1 S and measuring the inward current produced at the beginning of a subsequent command step to –50 mV. An example of the inward currents evoked at the beginning of the second step is shown in the box on the lower right. The normalized response was plotted as a function of the duration of the conditioning step and revealed a τ_{deinact} of 208.05 ms. B) The kinetics of inactivation were determined by varying the interval between fixed amplitude conditioning step to (–90 mV).
and command step (~50 mV). The interval was increased from 15 mS to 555 ms in 60 ms increments. An example of the inward currents evoked at the beginning of the second step is shown in the box on the lower right. The normalized response was plotted as a function of the duration of the conditioning step and revealed a \( \tau_{\text{inact}} \) of 56.1 ms.

Figure 7. BNST\(_{\text{ALG}} \) neurons exhibit a transient outward current that resembled the voltage-dependent potassium current \( I_A \). A) Upper trace, the dual-step protocol used to determine the activation curve for the voltage-dependent potassium current \( I_A \). An example of the outward currents evoked at the beginning of the second step is shown in the box on the lower right, and this current was completely blocked in the \( I_A \) channel blocker 4-AP (5 mM, inset). The activation curve of the normalized response plotted as a function of command voltage revealed a \( V_{1/2} \) of \(-3.1 \pm 2.7 \) mV. B) Upper trace, dual-step protocol used to determine the de-inactivation curve for the voltage-dependent potassium current \( I_A \). An example of the outward currents evoked at the beginning of the second step is shown in the box on the lower right. The de-inactivation curve of the normalized response plotted as a function of the conditioning voltage revealed a \( V_{1/2} \) of \(-70.4 \pm 2.4 \) mV.

Figure 8. De-inactivation and inactivation kinetics of \( I_A \) in BNST\(_{\text{ALG}} \) neurons. A) The kinetics of de-inactivation were determined by varying the length of the conditioning step to \((-100 \) mV\)) from 10 ms to 700 ms and measuring the outward current produced at the beginning of a subsequent command step to \(-25 \) mV. An example of the outward currents evoked at the beginning of the second step is shown in the box on the lower right. The normalized response was plotted as a function of the duration of the conditioning step and revealed a \( \tau_{\text{d deinact}} \) of 34.6 ms. B) The kinetics of inactivation were determined by varying the interval between fixed amplitude conditioning step to \((-100 \) mV\)) and command step \((-25 \) mV\)). The interval was increased from 0 ms to 900 ms in 100 ms increments. An example of the outward currents evoked at the beginning of the second step is shown in the box on the lower right. The normalized response was plotted as a function of the duration of the conditioning step and revealed a \( \tau_{\text{inact}} \) of 211.41 ms.
Figure 9. BNST\textsubscript{ALG} neurons exhibit an inwardly rectifying potassium current, $I_{K(IR)}$, and a persistent inward sodium current, $I_{NaP}$. A) The voltage response to hyperpolarizing current in a representative Type III neuron before and during application of the $I_{K(IR)}$ channel blocker BaCl\textsubscript{2}. B) The current response to hyperpolarizing voltage steps in voltage clamp mode in a representative Type III neuron. BaCl\textsubscript{2} (500 μM) blocked the $I_{K(IR)}$ current. C) A representative example of the $I_{NaP}$ current recorded from a BNST\textsubscript{ALG} neuron. In response to a command voltage that ramped from 100 mV to +10 mV at a rate of 10 mV/s, a large inward current was observed with a $V_{1/2}$ of -39.4 ± 1.8 mV. This inward current was blocked by the sodium channel blocker, TTX (1 μM).
Table 1

<table>
<thead>
<tr>
<th>Type</th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td>29</td>
<td>55</td>
<td>16</td>
</tr>
<tr>
<td>RMP (mV)</td>
<td>-60 ± 0.59</td>
<td>-58 ± 0.49</td>
<td>-64 ± 1.07*</td>
</tr>
<tr>
<td>Re (MΩ)</td>
<td>452.6 ± 30†</td>
<td>377.4 ± 15.6</td>
<td>357.8 ± 38.1</td>
</tr>
<tr>
<td>τ (mS)</td>
<td>32.7 ± 3.1</td>
<td>31.44 ± 2.7</td>
<td>29.22 ± 2.0</td>
</tr>
<tr>
<td>Spike TH (mV)</td>
<td>-43.2 ± 0.5</td>
<td>-44.2 ± 0.6</td>
<td>-42.75 ± 0.8</td>
</tr>
<tr>
<td>Spike Amp (mV)</td>
<td>75.7 ± 3.9</td>
<td>82.0 ± 3.7</td>
<td>69.3 ± 4.9</td>
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<tr>
<td>Spike RT (mS)</td>
<td>0.44 ± 0.02</td>
<td>0.49 ± 0.03</td>
<td>0.42 ± 0.02</td>
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<tr>
<td>Spike DT (mS)</td>
<td>0.88 ± 0.05</td>
<td>1.04 ± 0.09</td>
<td>1.0 ± 0.12</td>
</tr>
<tr>
<td>Spike HW (mS)</td>
<td>0.95 ± 0.04</td>
<td>1.1 ± 0.09</td>
<td>0.96 ± 0.06</td>
</tr>
</tbody>
</table>

* Statistically significant from Types I and II.
† Statistically significant from Type II, but not type III.
Figure 1. The anterolateral group of the bed nucleus of the stria terminalis (BNSTALG), as defined by Dong et al. 2001, is outlined by the thicker hatched line. In the present studies, neurons were recorded from the lateral BNSTALG regions outlined in gray. Neurons were recorded from regions dorsal to the anterior commissure, including the anterolateral area proper, the oval nucleus, rhomboid nucleus, and the juxtacapsular nucleus. Abbreviations: AC: anterior commissure; AV: anteroventral area; AL: anterolateral area; BNST: bed nucleus of the stria terminalis; FU: fusiform nucleus; IC: internal capsule; JU: juxtacapsular nucleus; LSV: ventral lateral septal nucleus; OV: oval nucleus; SC: subcommissural zone.
Figure 2. Three electrophysiologically distinct cell types (I-III) are observed in the BNST_{ALG} differ in their response to depolarizing and hyperpolarizing current injection. A) Type II neurons respond to depolarizing current injection with an initial burst of spikes followed by a more regular firing pattern, while types I and III fired with a regular firing pattern. B) Type I and II neurons exhibited a depolarizing sag in response to hyperpolarizing current injection that was accompanied by a rebound depolarization on the offset of current injection. In Type II neurons this rebound event was often accompanied by spikes. Type III neurons did not exhibit the depolarizing sag, but instead exhibited a fast anomalous rectification at more hyperpolarized potentials.

177x238mm (96 x 96 DPI)
Figure 3. The depolarizing sag in the BNST\textsubscript{ALG} activated with different time constants. A) Frequency distribution of time constant values for the depolarizing sag across all BNST\textsubscript{ALG} neurons. B) Example in current clamp mode (CC) of fast and slowly activating depolarizing sags. C) Examples in voltage clamp mode (VC) of fast and slowly activating inward currents mediating the fast and slowly activating depolarizing sags. D) The time constant of the inward current mediating the depolarizing sag decreased as neurons were stepped to more hyperpolarized levels from $-60$ mV.
Figure 4. An $I_h$-like inward current mediated the depolarizing sag in BNST$_{ALG}$ neurons. A) The dual step protocol used to determine current activation properties. Neurons were stepped from $-100$ to $-45$ mV and then stepped to $-85$ mV. Tail current analyses were conducted on the current produced at the beginning of the second step. B) An example of the current response induced by the protocol described in A. The tail current induced at the beginning of the second step is magnified in the box on the lower right. This tail current was completely blocked in 5 mM of the $I_h$ channel blocker, CsCl (inset). C) The activation properties of the $I_h$-mediated inward current. The normalized tail current is plotted as a function of the voltage attained in the conditioning step, and exhibited a $V_{1/2}$ of $-80.13 \pm 0.5$ mV.
Figure 5. BNST_{AOL} neurons exhibit an inward current with properties of the low threshold calcium current, I_{T}. A) Upper trace, the activation curve used to elicit the low threshold calcium current, I_{T}. An example of the inward currents evoked at the beginning of the second step is shown in the box on the lower right. The current was completely blocked by the I_{T} channel blocker NiCl_{2} (5 mM, inset). The activation curve revealed a V_{1/2} of $-50.00 \pm 0.46$ mV. B) Upper trace, the dual step protocol used to determine the de-inactivation curve for the low threshold calcium current, I_{T}. An example of the inward currents evoked at the beginning of the second step is shown in the box on the lower right. The de-inactivation curve of the normalized response plotted as a function of the conditioning voltage revealed a V_{1/2} of $-77.65 \pm 0.67$ mV.
Figure 6. De-inactivation and inactivation kinetics of the low threshold calcium current, \( I_T \).

A) The kinetics of de-inactivation were determined by varying the length of the conditioning step to \((-100\, \text{mV})\) from 100 ms to 1 s and measuring the inward current produced at the beginning of a subsequent command step to \(-50\, \text{mV}\). An example of the inward currents evoked at the beginning of the second step is shown in the box on the lower right. The normalized response was plotted as a function of the duration of the conditioning step and revealed a deinact of 208.05 ms.

B) The kinetics of inactivation were determined by varying the interval between fixed amplitude conditioning step to \((-90\, \text{mV})\) and command step \((-50\, \text{mV})\). The interval was increased from 15 ms to 555 ms in 60 ms increments. An example of the inward currents evoked at the beginning of the second step is shown in the box on the lower right. The normalized response was
plotted as a function of the duration of the conditioning step and revealed a $\tau_{\text{inact}}$ of 56.1 ms.
BNSTALG neurons exhibit a transient outward current that resembled the voltage-dependent potassium current $I_A$. A) Upper trace, the dual-step protocol used to determine the activation curve for the voltage-dependent potassium current $I_A$. An example of the outward currents evoked at the beginning of the second step is shown in the box on the lower right, and this current was completely blocked in the $I_A$ channel blocker 4-AP (5 mM, inset). The activation curve of the normalized response plotted as a function of command voltage revealed a $V_{1/2}$ of $-3.1 \pm 2.7$ mV. B) Upper trace, dual-step protocol used to determine the de-inactivation curve for the voltage-dependent potassium current $I_A$. An example of the outward currents evoked at the beginning of the second step is shown in the box on the lower right. The de-inactivation curve of the normalized response plotted as a function of the conditioning voltage revealed a $V_{1/2}$ of $-70.4 \pm 2.4$ mV.
Figure 8. De-inactivation and inactivation kinetics of $I_A$ in BNSTALG neurons. A) The kinetics of de-inactivation were determined by varying the length of the conditioning step to $(-100 \text{ mV})$ from 10 ms to 700 ms and measuring the outward current produced at the beginning of a subsequent command step to $-25 \text{ mV}$. An example of the outward currents evoked at the beginning of the second step is shown in the box on the lower right. The normalized response was plotted as a function of the duration of the conditioning step and revealed a $t_{\text{deinact}}$ of 34.6 ms. B) The kinetics of inactivation were determined by varying the interval between fixed amplitude conditioning step to $(\sim 100 \text{ mV})$ and command step $(\sim 25 \text{ mV})$. The interval was increased from 0 ms to 900 ms in 100 ms increments. An example of the outward currents evoked at the beginning of the second step is shown in the box on the lower right. The normalized response was plotted...
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