Responses to GABA A Receptor Activation Are Altered in NTS Neurons Isolated From Renal-Wrap Hypertensive Rats

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Responses to $GABA_A$ Receptor Activation Are Altered in NTS Neurons Isolated From Renal-Wrap Hypertensive Rats

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Abstract—The inhibitory amino acid GABA is a potent modulator of the spontaneous discharge and the responses to afferent inputs of neurons in the nucleus of the solitary tract (NTS). To determine if responses to activation of $GABA_A$ receptors are altered in hypertension, $GABA_A$ receptor–evoked whole cell currents were measured in enzymatically dispersed NTS neurons from 33 normotensive (NT, 109±4 mm Hg, n=7) and 24 hypertensive (HT, 167±5 mm Hg, n=24) rats. $GABA_A$ receptor–evoked currents reversed at the calculated equilibrium potential for chloride and were blocked by bicuculline (n=6). Membrane capacitance was the same in neurons from NT (7.5±0.6 pF, n=62) and HT (6.8±0.6 pF, n=51) rats. The EC_{50} for peak GABA-evoked currents cells was significantly greater in neurons from HT (21.0±2.6 μmol/L, n=16) compared with NT rats (13.0±1.8 μmol/L, n=14, $P=0.01$). The EC_{50} of neurons exhibiting DiA labeling of presumptive aortic nerve terminals was no different than that observed in the nonlabeled cells (19.0±4.9 μmol/L, n=4). The time constant for desensitization of $GABA_A$-evoked currents was the same in neurons from HT (4.5±0.3 seconds, n=17) and NT rats (3.8±0.3 seconds, n=17, $P>0.05$). Repetitive pulse application of GABA revealed a more rapid decline in the evoked current in neurons from HT compared with NT rats. The amplitude of the 5th pulse of GABA (5-second duration, 2-second interval) was 21±2% the amplitude of the 1st pulse in NT rats (n=10) and 14±2% in HT rats (n=11, $P<0.05$). These alterations in $GABA_A$-receptor evoked currents could render the neurons less sensitive to $GABA_A$ receptor inhibition and influence afferent integration by NTS neurons in HT. **(*Hypertension*. 2003;42[part 2]:732-736.)**

Key Words: amino acid ■ baroreceptors ■ baroreflex ■ phosphorylation ■ hypertension, renal ■ neuroregulators

A variety of experimental approaches have established the importance within the nucleus of the solitary tract (NTS) of the inhibitory neurotransmitter γ-aminobutyric acid (GABA) as a modulator of cardiovascular and respiratory function.[1] $GABA_A$ receptors are the ubiquitous ligand-gated chloride ionophores responsible for most rapid inhibition within the central nervous system.[2–4] Within the NTS, activation of $GABA_A$ receptors inhibits virtually all neurons tested and results in an increase in arterial pressure, heart rate, and sympathetic outflow, effects consistent with inhibitory modulation of arterial baroreceptor reflexes.[1]

The function of $GABA_A$ receptors has been shown to be modulated by a variety of factors. Receptor number, subunit composition, and phosphorylation state are but a few of the ways that GABA receptor function can be altered after chronic exposure to alcohol, barbiturates, benzodiazepines, and GABA itself.[2–4] Alterations in the responses of NTS neurons to $GABA_A$ receptor activation could result in alterations in the integration of afferent inputs, reflex function, and resting cardiovascular parameters. The goal of the current study was to determine if the responses of isolated NTS neurons to activation of $GABA_A$ receptors are altered in hypertension.

Methods

General

Successful experiments were performed on adult (1 to 3 months), male Sprague-Dawley rats (375 to 500 g, Charles River Laboratories or Harlan Sprague-Dawley Inc). Rats were housed 2 per cage in a fully accredited (Association for Assessment and Accreditation of Laboratory Animal Care and the United States Department of Agriculture) laboratory animal room with free access to food and water. All rats were given at least 1 week to acclimate before being used for any procedures. The Institutional Animal Care and Use Committee approved all experimental protocols.

Chronic Hypertensive Model

Hypertension was induced using a 1-kidney renal-wrap procedure. Rats were anesthetized with medetomidine (0.5 mg/kg IP, Pfizer) and ketamine (75 mg/kg IP, Fort Dodge Laboratory). A figure-8 Grollman renal wrap and contralateral nephrectomy were performed on these animals.[5] Control animals were sham-operated rats that were similarly anesthetized and received a unilateral nephrectomy but no wrap of the contralateral kidney or rats with no surgical procedures before the day of the experiment. Since the responses of both groups of normotensive rats were identical, they were grouped together for analysis. Anesthesia was terminated by atipamezole (1 mg/kg IP, Pfizer) at the conclusion of the surgical procedures. Postoperative analgesics (Nubaine, given intramuscularly) were available as needed. In 4 rats, a second surgery was performed 2

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weeks after the first, and under the previously described anesthetic regimen and aseptic conditions, the anterograde fluorescent tracer DiA was applied to the aortic nerve to visualize baroreceptor synaptic terminals and neurons receiving these synaptic contacts as previously described.[6]

Dispersion of Caudal NTS Neurons

Experiments were performed 4 to 6 weeks after renal wrap or sham surgery. Two days before the experiment, an arterial catheter was placed in the femoral artery while the animal was under medetomine/ketamine anesthesia (0.5 mg/kg IP and 75 mg/kg IP, respectively). After a 2-day recovery period, the blood pressure of the conscious animal was measured by connecting the arterial catheter to a pressure transducer (Kobe) and displayed by means of MacLab or Cambridge Electronics Design A/D converters. Blood pressure was measured for 3 hours, and measurements made during the last hour were used as an index of mean arterial pressure (MAP). Conscious blood pressure was measured in every hypertensive (HT) rat (n=24) to ensure the rat was indeed HT. Conscious MAP was measured in 7 of 33 normotensive (NT) rats. The properties of cells obtained from NT rats in which MAP was measured were no different from those of cells in rats in which MAP was not measured therefore the data were pooled for analysis. All EC_{50} measurements were obtained from cells from rats with measured MAPs. Rats were anesthetized with isoflurane, and the brain stem was rapidly removed and placed in ice-cold Krebs buffer. The brain stem was cut into 440-μm-thick transversal sections centered around calamus, with the use of a vibratome (Warner Instrument Corp). The sections were incubated in the PIPES buffer with trypsin (Sigma, type XI, 3 to 7 mg/10 mL) for 60 minutes at ≈34°C. After the enzyme treatment, slices were rinsed 3 times with incubation solution and were maintained at room temperature (22° to 25°C) in the continuously oxygenated jar with the PIPES buffer.[7] Brain stem slices were placed on a glass slide, and the NTS region was identified and excised using a scalpel blade. The excised NTS region was gently triturated in a DMEMS buffer, with the use of a series of fire-polished pipettes. After trituration, an aliquot of the DMEMS/neuron suspension was placed in the perfusion bath and allowed to settle for 5 minutes, after which superfusion of the cells was begun with a normal physiological solution. All neurons were used within 10 hours after isolation.

Electrophysiology

Whole-cell patch-clamp recordings were performed on acutely dissociated NTS neurons bathed in an external solution consisting of (mmol/L) NaCl, 140; D-glucose, 33; HEPES, 10; KCl, 3; $CaCl_2$, 1.5; $MgCl_2$, 1.2 (pH 7.4 with NaOH; osmolarity 315 to 330 mOsm). Electrodes were formed from thin-walled quartz glass with a laser based P-2000 puller (Sutter Instrument Co) to resistances of 3 to 9 MΩ. Electrodes were filled with an internal solution with chloride concentration equimolar to that in the physiological solution and consisted of (mmol/L) CsCl, 120; $MgCl_2$, 2; TEA-Cl, 20; EGTA, 10; GTP, 0.1; ATP, 4; HEPES, 10 (pH 7.2 with CsOH; osmolarity 280 to 300 mOsm.). To maximize chloride currents and reduce sodium and potassium currents "drug" solutions contained (mmol/L): NaCl, 132; $BaCl_2$, 2; $MgCl_2$, 2; D-glucose, 33; TEA-Cl, 10; HEPES, 10 and TTX, 0.5 mmol/L. This combination of external and internal solutions gives a calculated chloride equilibrium potential of −0.7mV.[8] I-V curves were generated during GABA application by voltage ramps from −130 to +10 mV over 500 ms to determine the reversal potential of $GABA_A$ evoked currents. Cells were voltage clamped at −60 mV, using an Axopatch 200B amplifier (Axon Instruments). Currents were expressed as current density (pA/pF) to normalize for cells of different sizes. Currents were low-pass–filtered at 1 kHz, sampled at 10 kHz, and analyzed with the use of the pCLAMP8.1 software suite (Axon Instruments). If leak current was more than −50pA, data were not included in the analysis. At the amplifier, up to 80% series resistance compensation was applied. Before each drug application, a membrane test (Axon Instruments) was performed to monitor the possibility that access resistance changed over time or during different experimental conditions.

We repeated the drug application protocol originally described by Griffith and Murchison,[8] with minor modification. GABA was applied by gravity flow to isolated cells by multibarrel square glass pipettes, using a fast-step perfusion apparatus (Warner Instrument Corp). Fast application of GABA is critical as the response to GABA begins to desensitize quite rapidly. Each pipette was attached by tubing to separate valves connecting each pipette to up to 6 solution jars. The first pipette was positioned adjacent and as close as possible to the target cell. A steady stream of GABA-free, TTX-containing (0.5 μmol/L) bath solution abolished action potential discharge and protected the neuron from leakage from the second downstream drug-containing pipette. The second pipette was connected to 6 different concentrations of GABA. To apply GABA, a digital signal was sent to the Warner Perfusion Fast-Step by means of a Clampex recording protocol, and pipette assembly was rapidly moved, repositioning the TTX-containing pipette upstream to the cell and the GABA-ejecting pipette adjacent to the cell. After a user-defined interval, the pipette assembly was returned to the starting position.

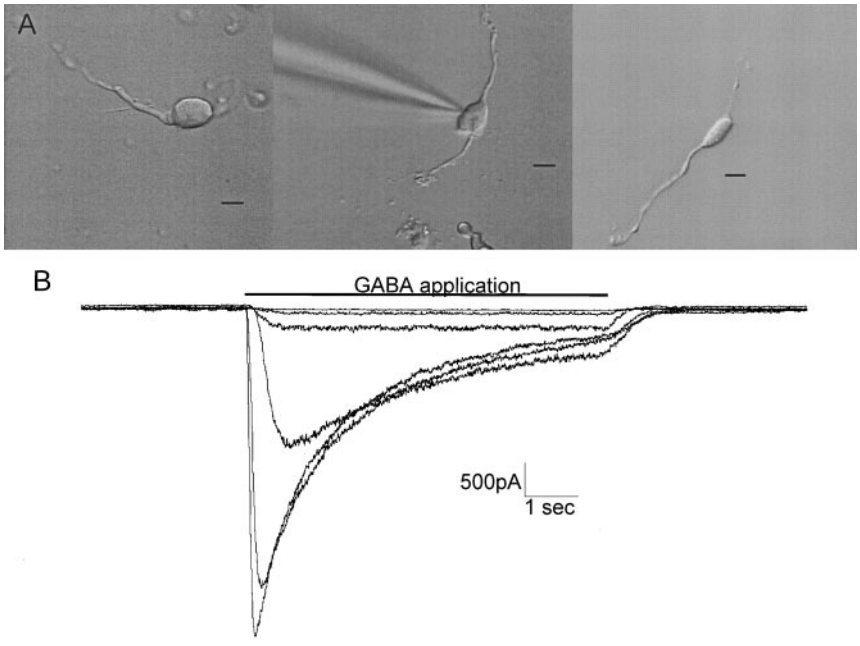

Figure 1. A, Captured images of 3 dispersed NTS neurons from different rats; shadow of patch recording electrode is visible in center. Cells in left and center panels isolated from NT rats and cell in right panel isolated from HT rat. Calibration bars, 10 μm. B, Responses of NTS neuron to 5-second applications of increasing concentrations of GABA (in μmol/L: 1, 3, 10, 30, 100, 300) during periods indicated by horizontal bar.

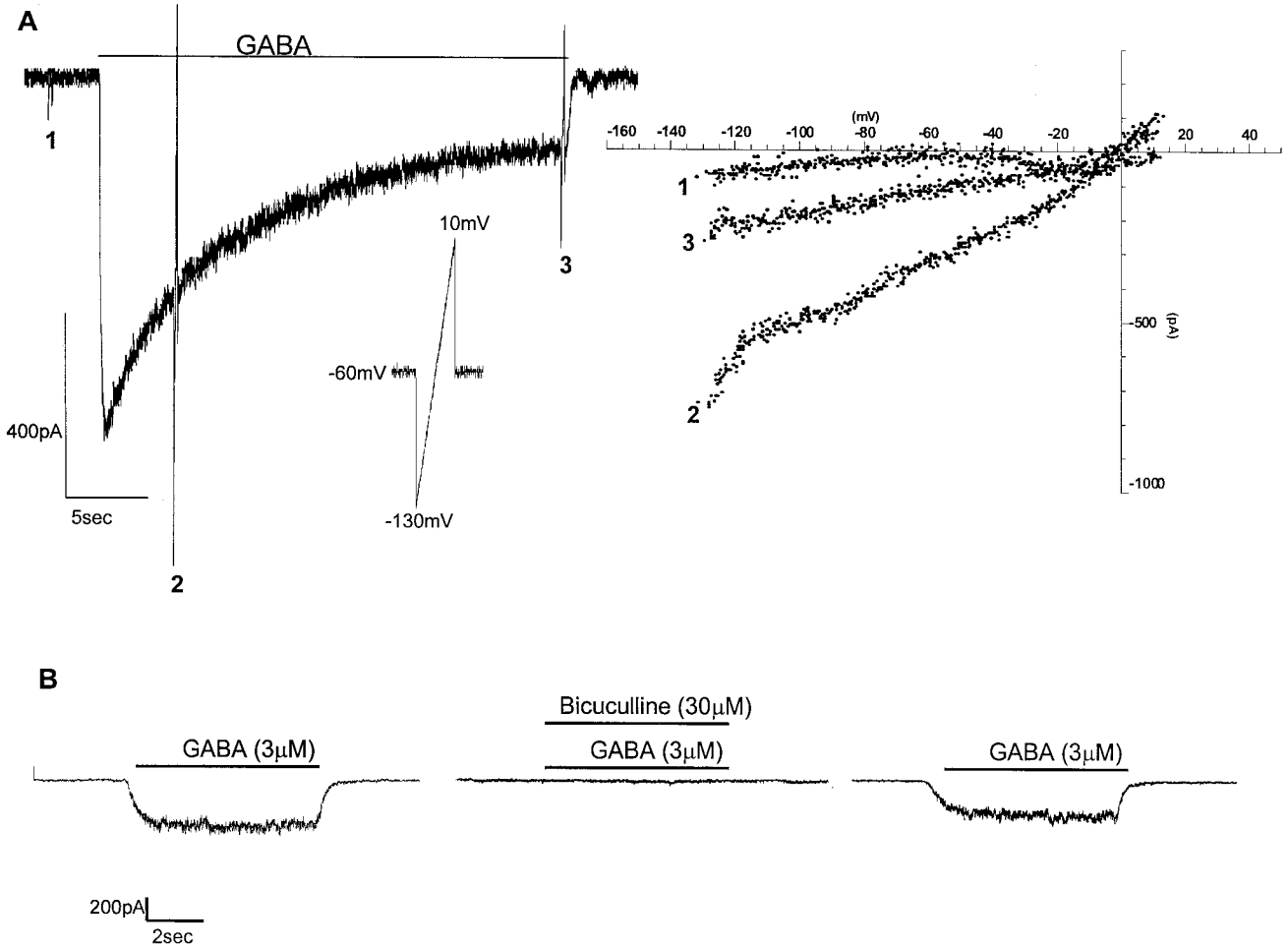

Figure 2. A, Left panel illustrates membrane current in NTS neuron from NT rat during voltage ramps (inset) delivered before drug delivery (1), 5 seconds after start (2), and immediately before the end (3) of application of 10 μmol/L GABA for 30 seconds during period indicated by horizontal bar. Right panel illustrates I-V relations at 3 corresponding points. B, Responses of NTS neuron from NT rat to application of GABA during period indicated by horizontal bars before (left), during (center), and after (right) application of the $GABA_A$ receptor antagonist bicuculline.

Data Analysis

Sequential dose-response relations were obtained during 5-second applications of 1, 3, 10, 30, 100, and 300 μmol/L GABA, with at least 2-minute intervals between all drug applications. Curves were fit using

$$I = I_{min} + \frac{I_{max} - I_{min}}{[1 + (A/EC_{50})^n]}$$

where I is the GABA-induced current, I_{max} the maximal GABA current, I_{min} the minimal GABA current, A the concentration of GABA, and n the Hill slope. Curve fits were obtained by a nonlinear regression, using a 4-parameter logistic function. Desensitization was observed during application of >10 μmol/L GABA, and a time constant describing the process was obtained by means of a single exponential fit. Statistical significance of differences between NTS neurons obtained from normotensive and hypertensive rats was determined by means of ANOVA with the Tukey or Dunn tests used for post hoc comparisons. All values are expressed as mean±SEM, and significance was accepted at $P<0.05$.

Results

Data were obtained from 33 normotensive (NT, MAP 109±4 mm Hg, n=7) and 24 hypertensive (HT, MAP 167±5 mm Hg) rats ($P<0.001$). Examples of dispersed NTS neurons are provided in Figure 1. The membrane capacitance of neurons provides a rough index of cell size, and there was no difference in neurons obtained from NT (7.52±0.55 pf, n=62) compared with HT (6.84±0.65 pf, n=51, $P>0.05$). There was no difference between neurons from NT and HT rats in the reversal potential of the $GABA_A$ receptor–evoked current determined by I-V curves obtained during application of 10 μmol/L GABA (NT, 0.3±1 mV, n=6; HT, −1±.06 mV, n=4; calculated reversal potential for chloride based on bath and pipette compositions was −0.7 mV, Figure 2A). $GABA_A$ receptor–evoked currents evoked by 3 μmol/L GABA were completely abolished after application of 30 μmol/L bicuculline (n=6) (Figure 2B).

Dose-Response Relations

Increasing concentrations of GABA were sequentially applied at 2- to 3-minute intervals (Figure 1B). At concentrations >10 μmol/L, there was a noticeable decay in the peak current despite continued application of GABA. At least 2 minutes was allowed to elapse between each 5-second application to minimize the effects of this desensitization that

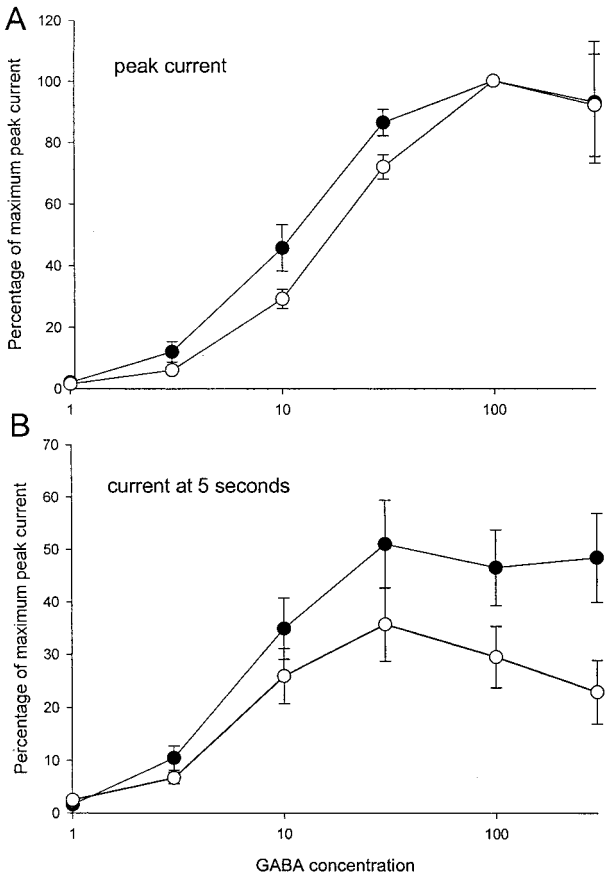

Figure 3. Dose-response relations for GABA in NTS neurons isolated from NT (●) and HT (○) rats. A, Curves of peak current density responses as percentage of maximum response. B, Curves of current density 5 seconds after onset of GABA application.

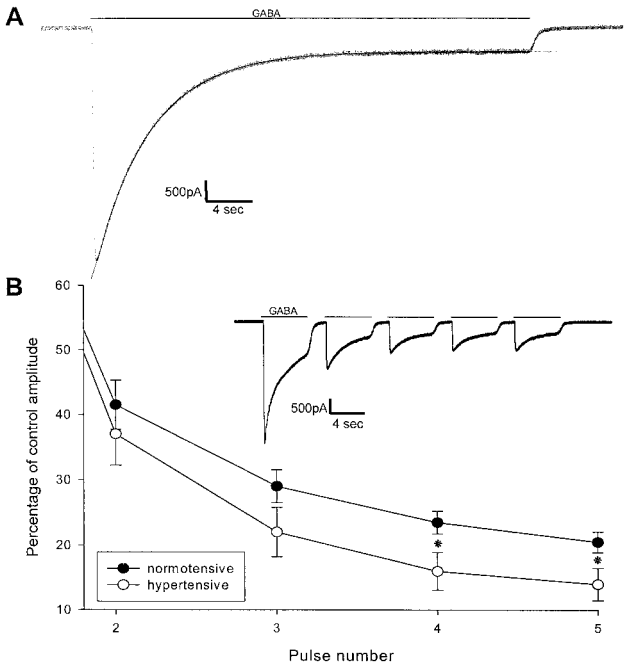

Figure 4. A, Response to 30-second application of 100 μmol/L GABA to NTS neuron from normotensive rat during period indicated by horizontal bar. Line through data indicates curve fit by single exponential equation to evaluate time constant of desensitization. B, Decline in response during repetitive application of 1 mmol/L GABA to NTS neuron from hypertensive rat, as illustrated in inset. Five pulses of GABA were applied (5-second duration with 2-second interval) during periods indicated by horizontal bars. Peak current density of pulses 2 to 5 were normalized to maximum peak current measured during first pulse. *$P<0.05$.

developed during one application from influencing the response to a subsequent application. Sequential application of increasing GABA concentrations revealed a rightward shift in the GABA dose-response curve in HT rats measured at the peak of the response and 5 seconds later (Figure 3). The EC_{50} of the peak current density evoked by GABA was 13.03±1.75 μmol/L in neurons from NT rats (n=14) and 21.03±2.63 μmol/L in neurons from HT rats (n=16, $P=0.02$) (Figure 3A). This difference was even more pronounced when examining GABA-evoked currents 5 seconds after the onset of application (Figure 3B); however, the shape of the curve did not permit fitting to derive an "adapted" EC_{50}. The dose-response curves obtained in cells from HT rats exhibiting DiA labeling were no different from the rest of the HT population (EC_{50}, 19±5 μmol/L, n=4).

The decay of GABA-evoked currents at concentrations >10 μmol/L indicates desensitization of GABA-evoked currents occurs in neurons from NT and HT rats. Alterations in desensitization could lead to a shift in EC_{50}; therefore, we looked at this process in more detail.

Time-Dependent Changes in GABA Receptor–Evoked Responses

Previous studies have reported time-dependent reductions in GABA currents with time due to depletion of intracellular ATP.[9] To determine if run-down of GABA-evoked currents contributed to the differences in EC_{50} between NT and HT rats, GABA was applied (1 mmol/L, 2-second duration) at the onset of a recording and every 5 minutes for 25 minutes. The peak current density after 25 minutes of recording was 94±11% of the value obtained at the onset of the recording in NT rats (n=8) and 95±3% in HT rats (n=3) ($P>0.05$).

Desensitization was examined during 30-second applications of 100 μmol/L GABA. A single exponential curve fit of the decay in current from peak amplitude revealed no difference in the time constant of desensitization, comparing neurons from NT rats (3830±339 ms, n=17) with neurons from HT rats (4514±298 ms, n=17, Figure 4A). There was also no difference in the peak current density response to 100 μmol/L GABA of neurons from NT rats (419±51 pA/pf, n=26) with neurons from HT rats (443±41 pA/pf, n=26).

To examine responses to repetitive applications of GABA, five 5-second pulses of 1 mmol/L GABA were applied at 2-second intervals (Figure 4B). There was a significant reduction in the GABA-evoked currents during the 4th and 5th pulses in neurons from HT rats. In NT rats, the peak current amplitude of the 5th pulse was 21±2% (n=10) of that measured during the 1st pulse. In HT rats, the amplitude of the 5th pulse was 14±2% (n=11, $P<0.05$) that of the 1st pulse.

Discussion

These results demonstrate that the responses of NTS neurons to activation of $GABA_A$ receptors are reduced in HT rats. Activation of $GABA_A$ receptors inhibits NTS neurons receiving arterial baroreceptor, and most other visceral afferent inputs and activation of $GABA_A$ receptors during visceral afferent stimulation have been described.[1] A reduction of this inhibition in HT rats in the absence of any other changes would be expected to enhance excitatory transmission through the NTS.

An important question is if the changes observed are specific for neurons receiving baroreceptor inputs. The identification of neurons with somatic DiA appositions is suggestive but not demonstrative. The answer to this question can best be answered by identification of the stimulus that initiates reduced sensitivity to GABA and this has yet to be determined. It is possible that excitatory and/or inhibitory synaptic inputs from peripheral or central sites could alter $GABA_A$ receptor function. It is also possible that circulating hormones associated with HT (catecholamines, angiotensin II) might initiate the alterations. The precise mechanism(s) that initiate and sustain the alterations are an important determinant of the specificity of the observed changes. If the stimulus is a specific afferent input, one would predict that changes occur only in those neurons receiving the afferent input; whereas if the stimulus is a hormone, alterations in $GABA_A$ receptor–evoked responses may be observed in a more widespread population of neurons. The present results suggest but do not conclusively prove the latter possibility.

Mechanisms for reduced sensitivity to GABA are as numerous as are the possible triggers for such changes. In response to other perturbations, $GABA_A$ receptors have been shown to undergo changes in subunit composition, changes in the number and/or affinity of binding sites, and changes in intracellular calcium and/or phosphorylation state leading to enhanced or reduced conductance.[3,4] All of these possibilities remain avenues for future studies.

Although our data indicate that desensitization during a single application of GABA was not different in neurons from NT compared with HT rats, there was a difference in the responses to repetitive application of GABA. There are several possible explanations for this observation. A reduced ability to recover from desensitization,[10] an alteration in the chloride equilibrium potential and/or altered activity of chloride exchange mechanisms,[11] and alterations in phosphorylation state[12,13] could contribute to what appears to be a cumulative effect of brief GABA applications. The functional significance of this observation may be manifested when the GABAergic inputs are pulsatile as opposed to tonic in nature.

Perspectives

NTS neurons are less sensitive to $GABA_A$ receptor–mediated inhibition in HT. In the absence of any other changes, reduced GABAergic inhibition of NTS neurons would lead to increased spontaneous discharge and enhanced responses to activation of afferent inputs.[1] However, we have previously demonstrated in this model of HT that NTS neurons receiving aortic baroreceptor afferent inputs exhibit normal discharge frequencies and responses to aortic nerve stimulation.[14] We have also demonstrated enhanced responses to activation of $GABA_B$ receptors in this model of HT,[15] and this may mitigate the consequences of reduced $GABA_A$-mediated inhibition.

Acknowledgments

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References

1. Mifflin SW. What does the brain know about blood pressure? *News Physiol Sci*. 2001;16:266–271.
2. Rabow LE, Russek SJ, David H. Farb DH. From ion currents to genomic analysis: recent advances in $GABA_A$ receptor research. *Synapse*. 1995; 21:189–274.
3. Mehta AK, Ticku MK. An update on $GABA_A$ receptors. *Brain Res Rev*. 1999;29:196–217.
4. Gaiarsa JL, Caillard O, Ben-Ari Y. Long-term plasticity at GABAergic and glycinergic synapses: mechanisms and functional significance. *Trends Neurosci*. 2002;25:564–570.
5. Grollman A. A simplified procedure for inducing chronic renal hypertension in the mammal. *Proc Soc Exp Biol Med*. 1944;57:102–104.
6. Mendelowitz D, Yang M, Andersen MC, Kunze DL. Localization and retention in vitro of fluorescently labeled aortic baroreceptor terminals on neurons from the nucleus tractus solitarius. *Brain Res*. 1992;581: 339–343.
7. Kay AR, Wong RKS. Isolation of neurons suitable for patch-clamping from adult mammalian central nervous systems. *J Neurosci Methods*. 1986;16:227–238.
8. Griffith WH, Murchison DA. Enhancement of GABA-activated membrane currents in aged Fisher 344 rat basal forebrain neurons. *J Neurosci*. 1995;15:2407–2416.
9. Shirasaki T, Aibara K, Akaike N. Direct modulation of $GABA_A$ receptor by intracellular ATP in dissociated nucleus tractus solitarii neurons of rat. *J Physiol*. 1992;449:551–572.
10. Mozrzymas JW, Cherubini E. Changes in intracellular calcium concentration affect desensitization of $GABA_A$ receptors in acutely dissociated P2-P6 Rat hippocampal neurons. *J Neurophysiol*. 1998;79: 1321–1328.
11. Ling DSF, Benardo LS. Activity-dependent depression of monosynaptic fast IPSCs in hippocampus: contributions from reductions in chloride driving force and conductance. *Brain Res*. 1995;670:142–146.
12. Gyenes M, Wang Q, Gibbs TT, Farb DH. Phosphorylation factors control neurotransmitter and neuromodulator actions at the γ-aminobutyric acid type A receptor. *Mol Pharmacol*. 1994;46:542–549.
13. Leidenheimer NJ, McQuilkin SJ, Hahner LD, Whiting P, Harris RA. Activation of protein kinase C selectively inhibits the γ-aminobutyric $acid_A$ receptor: role of desensitization. *Mol Pharmacol*. 1992;41: 1116–1123.
14. Zhang J, Mifflin SW. Integration of aortic nerve inputs in hypertensive rats. *Hypertension*. 2000;35:430–436.
15. Durgam VR, Vitela M, Mifflin SW. Enhanced $GABA_B$ receptor agonist responses and mRNA within the nucleus of the solitary tract in hypertension. *Hypertension*. 1999;33:530–536.