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Influence of GABA on neurons of the gustatory zone of the rat nucleus of the solitary tract

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The role of γ-aminobutyric acid (GABA) as an inhibitory neurotransmitter in the rostral, gustatory zone of the nucleus of the solitary tract (rNST) was examined using whole cell recordings in brain slices of the adult rat medulla. Superfusion of GABA resulted in a concentration-dependent reduction in input resistance in 68% of the neurons in rNST. The change in input resistance was often accompanied by membrane hyperpolarization. The effect of GABA was a direct action on the postsynaptic membrane since it could be elicited when synaptic transmission was blocked by tetrodotoxin or in a low Ca^{2+} and high Mg^{2+} perfusing solution. The mean reversal potential of the GABA effect was about -60 mV, determined by applying GABA at different holding potentials, or from the intersection of current–voltage curves measured in control saline and saline containing GABA. When neurons were separated into groups based on intrinsic membrane properties, some neurons in each group responded to GABA. Superfusion of the slices with either the $GABA_A$ agonist, muscimol, or the $GABA_B$ agonist, baclofen, caused a decrease in input resistance accompanied by membrane hyperpolarization. The $GABA_A$ antagonist bicuculline either totally or partially blocked the neuronal response to GABA and blocked the response to muscimol but did not antagonize responses to baclofen. Superfusion of the $GABA_B$ antagonist phaclofen depressed the membrane responses to GABA. The use of the $GABA_A$ and $GABA_B$ agonists and antagonists demonstrates that some neurons in rNST have both $GABA_A$ and $GABA_B$ receptors. Since most rNST neurons studied respond to GABA, inhibition probably plays a major role in sensory processing by the rNST.

INTRODUCTION

The rostral extent of the nucleus of the solitary tract (rNST) is the site of termination of afferent gustatory fibers[4,22]. Morphological analysis of Golgi stained material of the gustatory zone of the rat rNST shows that it contains at least three neuron types[28,29]. Fusiform neurons are characterized by an elongated soma and two large primary dendrites; multipolar neurons have a stellate-shaped soma and three to five primary dendrites; ovoid neurons have small soma diameters and two or three primary dendrites. The small ovoid neurons connect locally in the medulla whereas the multipolar and fusiform neurons project rostrally to the parabrachial nucleus[28,55]. Multipolar neurons are reportedly the predominant rostral projection neuron in the rat[27].

Using whole cell recordings in slice preparations of

the rat gustatory NST we have shown that neurons can also be separated into groups based on their neurophysiological discharge pattern[5]. Using a hyperpolarization-depolarization pulse paradigm to distinguish cell types, we characterized four neural groups. Hyperpolarization of Group I neurons altered the repetitive discharge pattern initiated by membrane depolarization to an irregular pattern. Hyperpolarization of Group II neurons either delayed the occurrence of the first action potential, or increased the length of the first interspike interval in the action potential train produced by membrane depolarization. Hyperpolarization least affected the discharge pattern of Group III neurons. Hyperpolarization of Group IV neurons shortened the length of the action potential burst produced by membrane depolarization. The neurons in these four groups also differed in other passive membrane properties[5].

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It is apparent, therefore, that membrane hyperpolarization of rNST neurons has a marked influence on the pattern of action potentials initiated by depolarization. In vivo membrane hyperpolarization is presumably the result of inhibitory synaptic activity. Because the inhibitory neurotransmitter γ-aminobutyric acid (GABA) has been shown to play a major role in the control of cardiovascular, respiratory and swallowing activity in the caudal NST[10,26,31,44,53] and because neurons in the rNST of rat have been shown to be GABAergic using immunocytochemical techniques[28], we examined the influence of GABA on neurons of the gustatory rNST using whole cell recording in a brain slice preparation of the rat medulla.

MATERIALS AND METHODS

Tissue preparation

Adult rat rNST slices were prepared and maintained as described elsewhere[5]. Briefly, rats weighing $120-250 \times g$ were anesthetized with sodium pentobarbital (50 mg/kg), and the brainstem removed. Four, coronal, 400 μm slices containing the rostral 1.6 mm of the NST were cut on a Vibratome. After incubation in oxygenated, room temperature, physiological saline for at least one hour, a slice was transferred to a recording chamber with a wide-mouthed pipette. The slice was maintained at 32°C and superfused with physiological saline at a rate of 1.5–2.0 ml/min. The physiological saline contained (in mM): NaCl 124, KCl 5, $CaCl_2$ 2.5, $MgSO_4$ 1.3, $NaHCO_3$ 26, KH_2PO_4 1.25, glucose 25; the solution was gassed with 95% O_2, 5% CO_2 to give a pH of 7.4.

Neurophysiology

Whole cell recordings were made using the technique described by Blanton et al.[2]. Patch electrodes were pulled in two stages from 1.5 mm, outside diameter, borosilicate filament glass (WPI, TW150F50F-4) on a Narishige PP83 electrode puller, and had a tip resistance of 5–8 $M\Omega$ (bubble numbers of 5.8–6[34]). They were filled with a solution containing (in mM) K-gluconate 130, HEPES 10, EGTA 10, $CaCl_2$ 1, ATP 2, adjusted to a pH of 7.35 with KOH. The electrodes were positioned over the rNST, which was easily identified through the dissecting microscope when transluminated from below. The indifferent electrode was a Ag–AgCl wire connected to the extracellular solution via an agar bridge. After a successful recording, the position of the patch pipette was noted on a standard series of diagrams of the brain slices.

Data analysis

Once a gigaohm seal had been obtained and the patch ruptured, current was injected into the neurons using the bridge circuit of an Axoclamp 2A (Axon Instruments) in current clamp mode. This was balanced after breakthrough and was checked throughout the recording. Changes in neuronal input resistance were monitored by injecting negative constant current pulses (100 ms, 0.1 nA) into the neurons at a frequency of 0.15 Hz and the resultant changes in membrane potential were recorded continuously on a pen recorder at slow speed (see for example Fig. 2A). This pulse length was sufficient to charge the membrane to a steady state level (see Fig. 5). In addition, current stimulation protocols were performed and voltage data acquired and analyzed under computer control using the pCLAMP program (Axon Instruments) throughout the experiments. To be considered a response to 10^{-3} M GABA the input resistance of the neuron, measured at the point of maximum effect, had to decrease by at least 10% of control values and the membrane potential had to change by more than 1 mV. Data are presented as

means ± S.E. and statistical significance ($P < 0.05$) was assessed using paired t-tests unless otherwise indicated.

Pharmacology

With a system of valves, physiological saline containing either GABA ($10^{-4}-10^{-3}$ M), muscimol (10^{-3} M), bicuculline (10^{-4} M), baclofen (10^{-4} M) or phaclofen ($10^{-3}-1.5 \times 10^{-3}$ M) was superfused over the slices. Experimental saline containing the pharmacological agent was exchanged for the control saline for $\frac{1}{2}$ min, and took 3 min to arrive at the slice chamber. Control saline was then superfused over the slice for at least 4 min, before switching to another concentration of GABA or GABA receptor agonists and antagonists. All drugs were obtained from Sigma Chemical Co. except phaclofen, which was supplied by Research Biochemicals Incorporated. Drug doses used were based on those found effective by other investigators[17,25].

Neuron classification

As in previous studies[5,13], neurons were separated into groups using a current injection paradigm in which the neurons were depolarized following membrane hyperpolarization of increasing durations.

RESULTS

Whole cell recordings were made from over 200 neurons in 124 rNST slices obtained from 85 rats. Of these neurons 131 were studied because they had a stable resting membrane potential, a spike overshoot of at least 10 mV (26 mV, ±0.9, range 10–53), and an input resistance greater than 100 $M\Omega$. The mean depth
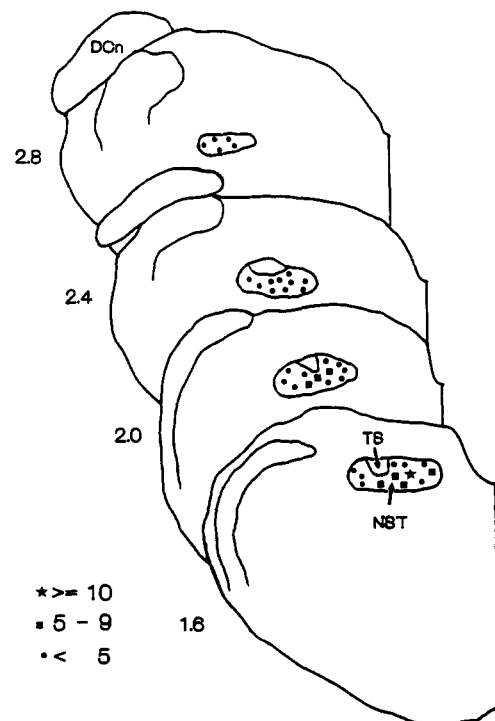

Fig. 1. Diagrams of 4 coronal slices of the brain stem containing the rostral pole of the NST. The recording site for all neurons is shown by different symbols representing the number of neurons recorded at each site. The numbers on the left indicate mm rostral to obex. DCn, dorsal cochlear nucleus; NST nucleus of the solitary tract; TS, tractus solitarius.

of the neurons in the slice was 77 μM (± 5.2, range 0 to 280). Mean resting membrane potentials of these neurons were -48 mV ($\pm - 0.76$, range -31 to -86). Action potential amplitude ranged from 43 to 107 mV (74 ± 1.1), with a mean duration measured at half amplitude of 1.4 ms (± 0.03). Input resistance, determined from responses to a 100 ms, -100 pA hyperpolarizing current pulse, varied between 151 and 1577 MΩ (517 ± 24.6). These values are similar to those reported by us and other investigators using whole cell recordings in brain slices[2,5,45,48].

Membrane responses to GABA

Superfusion of GABA (10^{-3} M) resulted in a reduction in input resistance in 89 of 131 neurons (68%), distributed throughout the rNST. The location of these neurons in coronal slices is identified in Fig. 1. Neurons that responded to GABA were situated at similar depths to neurons that did not respond to GABA
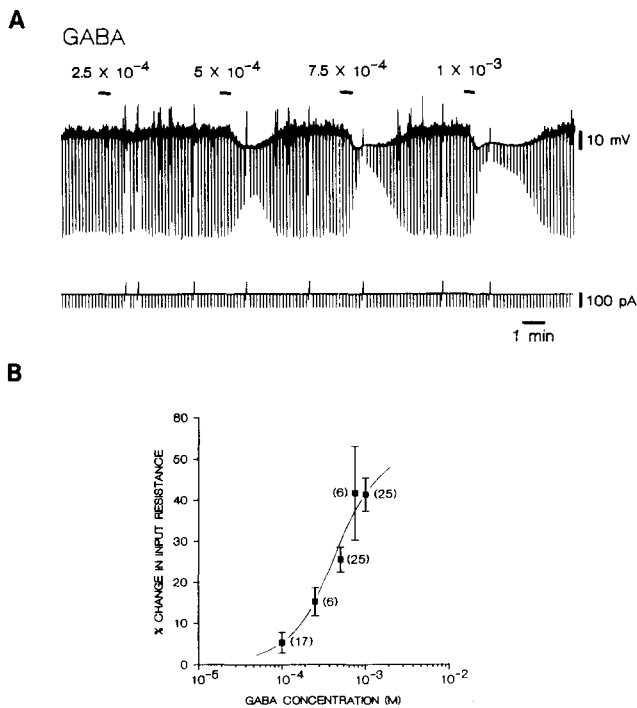

Fig. 2. A: membrane responses (upper trace) of a rostral NST neuron to constant current hyperpolarizing pulses (lower trace) applied through the patch electrode during superfusion of the slice with different concentrations of GABA (horizontal bars). Between applications the slice was superfused with control saline. This neuron responded with increasing levels of membrane hyperpolarizations and reduction in input resistance (indicated by reductions in the hyperpolarizing membrane response) to higher concentrations of GABA. During the experiment computer generated current injection protocols used for analyses of changes in membrane properties were applied and interrupt the regular hyperpolarizing current pulses seen in the current trace. Resting membrane potential = -43 mV. B: concentration-response curves of % change in input resistance to increasing concentrations of GABA. Numbers of measurements at each concentration are shown in parentheses. The curve was fitted by eye. Bars = S.E. of mean.
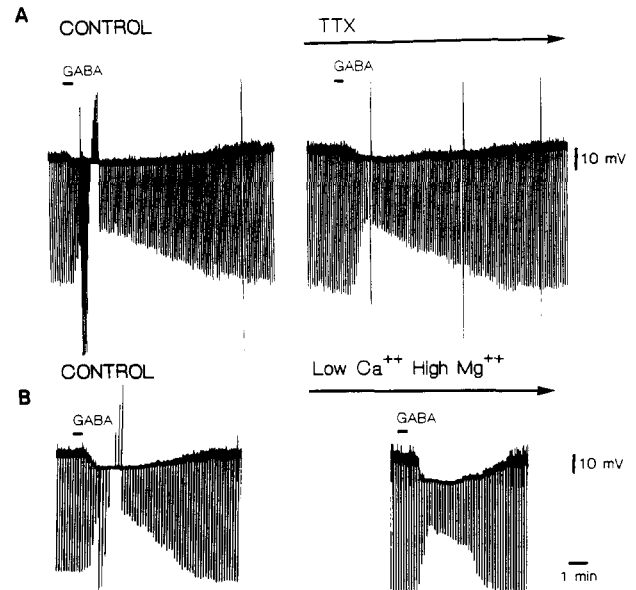

Fig. 3. A: membrane response of a rNST neuron to superfusion of 10^{-3} M GABA control saline and in the presence of 0.5×10^{-6} M TTX. Resting membrane potential = -52 mV. B: membrane response of a rNST neuron to superfusion of 10^{-3} M GABA in control saline and in the presence of low Ca^{2+} and high Mg^{2+} (0.2 mM Ca^{2+}, 11.4 mM Mg^{2+}) perfusing solution. Computer generated hyperpolarizing and depolarizing current pulses used to measure membrane characteristics interrupt the hyperpolarizing membrane responses in all traces. Resting membrane potential = -52 mV.

(mean depth of responders = 76 μM ± 6.5, range 0–280; mean depth of non-responders = 80 μM ± 8.7, range 0–250).

Application of a concentration series of GABA (1×10^{-4} to 1×10^{-3} M) revealed a dose-dependent reduction in input resistance (Fig. 2A). With 10^{-3} M GABA the extent of the reduction averaged 34 MΩ (± 2, range 13–86, $n = 82$). Membrane resistance returned to control levels within 3–5 min of termination of the GABA application. The change in membrane resistance was often accompanied by membrane hyperpolarization (mean hyperpolarization for 10^{-3} M GABA = -3.5mV $\pm - 0.3$, range -13 to -1.0, $n = 75$) (Fig. 2A).

A concentration–response curve of the reduction in input resistance produced by superfusion with GABA is shown in Fig. 2B. At least 3 GABA concentrations were used on each neuron, but not all concentrations were used on all neurons (number of observations shown in parentheses). For some neurons the lower concentrations did not affect membrane resistance but these have been included in the calculations of the mean value for each concentration.

The effect of GABA was a direct action on the postsynaptic membrane since it could be elicited when synaptic transmission was blocked by tetrodotoxin (TTX 0.5×10^{-6} M, $n = 6$) or in a low Ca^{2+} high Mg^{2+} (0.2

mM Ca^{2+}, 11.4 mM Mg^{2+}, $n = 11$) perfusing solution (Fig. 3A and B.). Analysis of the effect of GABA application on input resistance and membrane potential before and in the presence of TTX and low Ca^{2+} high Mg^{2+} revealed no significant change ($P > 0.15$).

The GABA reversal potential was found by applying GABA at different holding potentials (Fig. 4A), as well as from the intersection of current–voltage curves (Fig. 4B) measured in control saline and saline containing 10^{-3} M GABA. Using both these methods the mean reversal potential was -60.4 mV ± 1.7 (range -43 to -96, $n = 41$). The distribution of the reversal potentials is shown in Fig. 4C, together with their normal

distribution showing that most of the neurons tested have reversal potentials around -60 mV.

Membrane responses of different groups of neurons to GABA

Neurons were separated into groups using a current injection protocol consisting of a 200 pA hyperpolarizing pulse of different lengths (50–200 ms) immediately followed by a long (1200 ms, 100 pA) depolarizing pulse (Fig. 5A–D). This method has been used previously by our laboratory to characterize rNST neurons[5]. Of the total neurons, 10 were classified as Group I, 53 as Group II, 50 as Group III and 18 as Group IV.
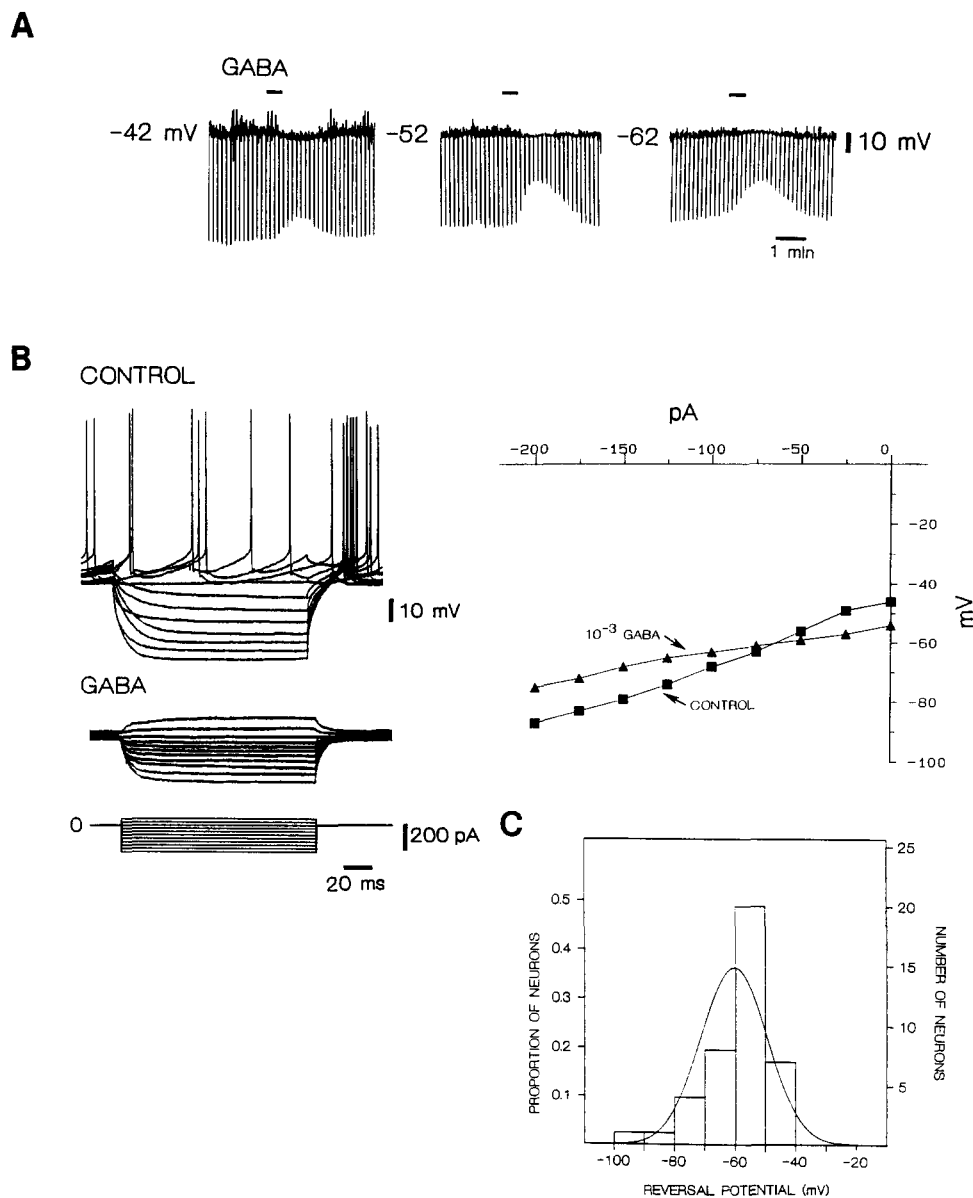

Fig. 4. A: membrane response of a rNST neuron to superfusion of 10^{-3} M GABA in control saline at resting membrane potential levels and after the membrane potential had been hyperpolarized by current injection to a level of -52 and -62 mV. The hyperpolarization produced by GABA reverses to become a depolarization at -62 mV. B: current–voltage plot of a neuron in control saline and in saline containing 10^{-3} M GABA. The membrane responses are shown on the left. Resting membrane potential = -46 mV. C: distribution of the reversal potentials for 41 rNST neurons. A normal distribution has been fitted to these data and has a peak value close to -60 mV.
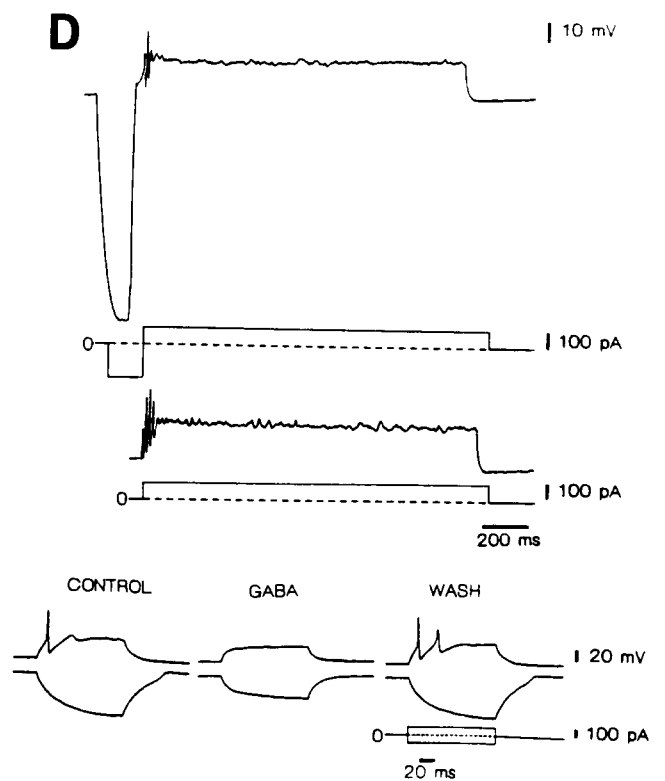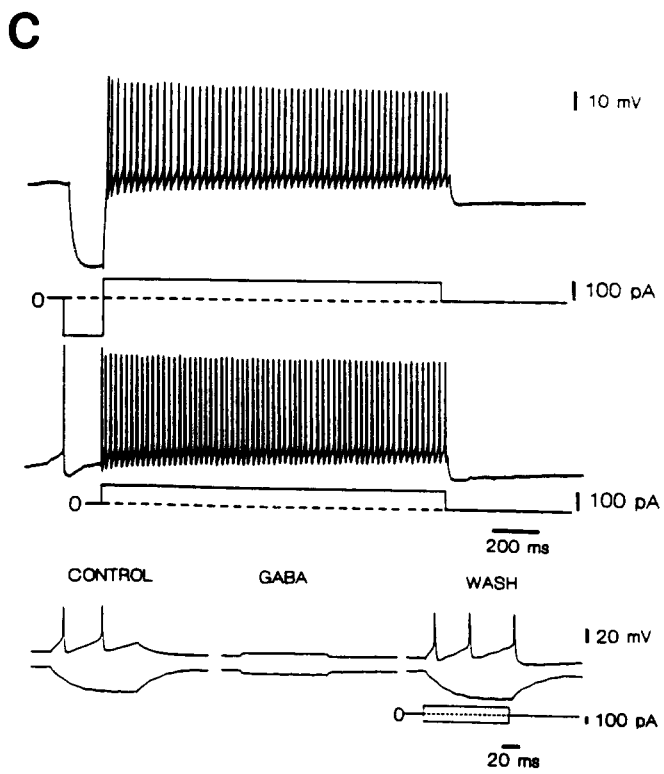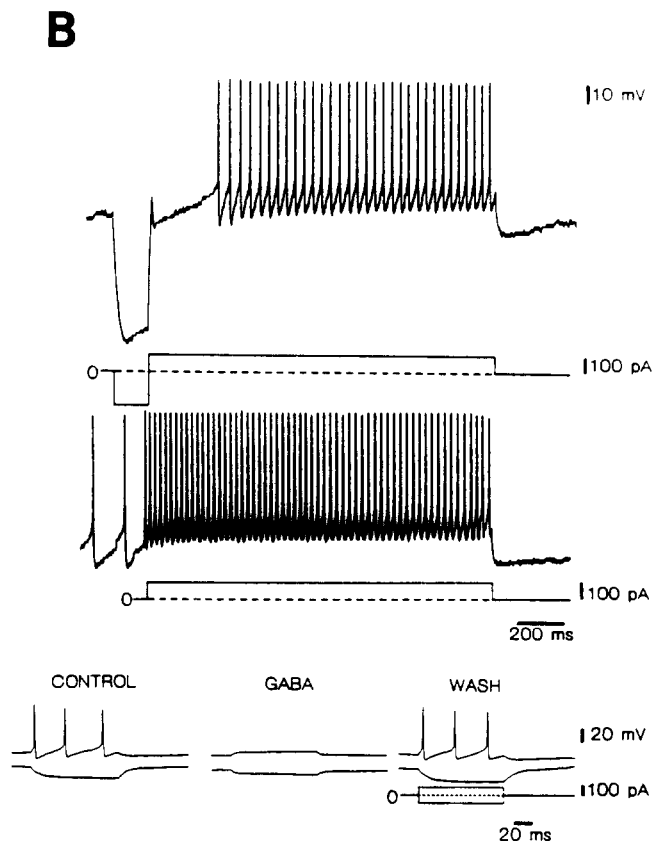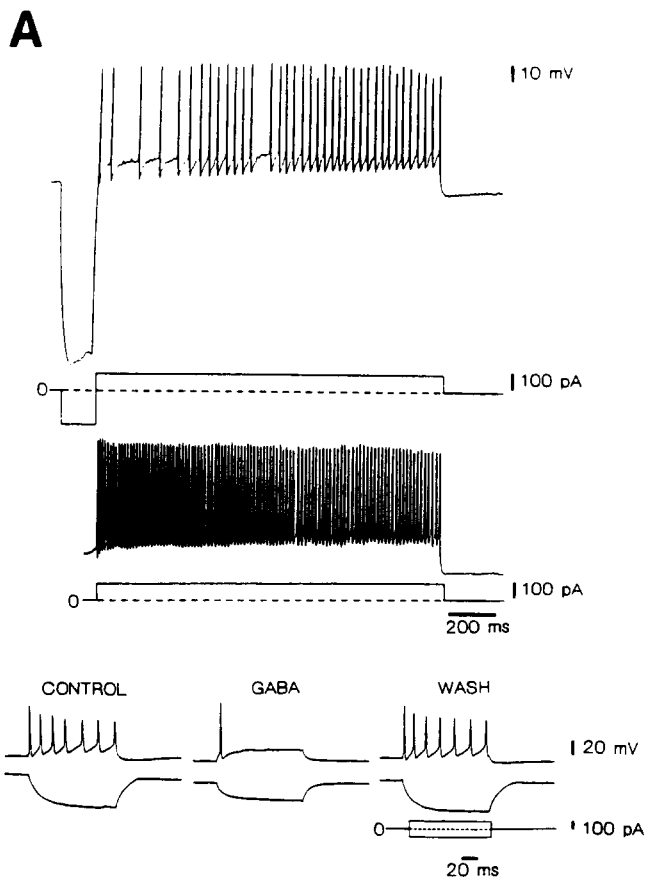
A

B

C

D

TABLE I

Effects of 10^{-3} GABA on neuron groups in the rostral NST

Group	n	% Neurons responding
I	10	50
II	53	76
III	50	62
IV	18	72

Neurons in all groups were influenced by 10^{-3} M GABA (Fig. 5A–D, lower panels), but not all the neurons in each group responded to GABA (Table I). There was no significant difference in the effect of GABA on the input resistance (analysis of variance, $F_{1,3} = 2.2$, $P = 0.09$) or membrane potential (analysis of variance, $F_{1,3} = 0.15$, $P = 0.93$) across the four neuron groups.

Differentiation of GABA receptor types using agonists and antagonists

GABA is known to activate at least two distinct receptors: $GABA_A$ receptors coupled to Cl^- channels and $GABA_B$ receptors coupled to a K^+ channel[3,17]. To find out what types of GABA receptor exist on neurons of the rNST, we superfused the slices with either the $GABA_A$ agonist muscimol or the $GABA_B$ agonist baclofen. Both muscimol (1×10^{-3} M) and baclofen (1×10^{-4} M) caused a decrease in input resistance accompanied by membrane hyperpolarization (Fig. 6A). Seventeen neurons that responded to 10^{-3} M GABA, were tested with muscimol and baclofen. All 17 responded to muscimol and 11 of these responded to baclofen as well. Thus, of the rNST neurons that respond to GABA, many respond to muscimol and baclofen (Fig. 6A) while others respond only to muscimol (Fig. 6B).

To further clarify the role of $GABA_A$ and $GABA_B$ receptors in synaptic processing in the rNST we used their respective antagonists. In 11 neurons that responded to 10^{-3} M GABA, the $GABA_A$ antagonist bicuculline (1×10^{-4} M) totally blocked the reduction in input resistance produced by GABA ($n = 11$, Fig. 7b). In other neurons responding to 10^{-3} M GABA, bicuculline partially blocked the GABA induced reduction of input resistance (mean reduction compared with control value for GABA = 42% ±11, range 17–85,
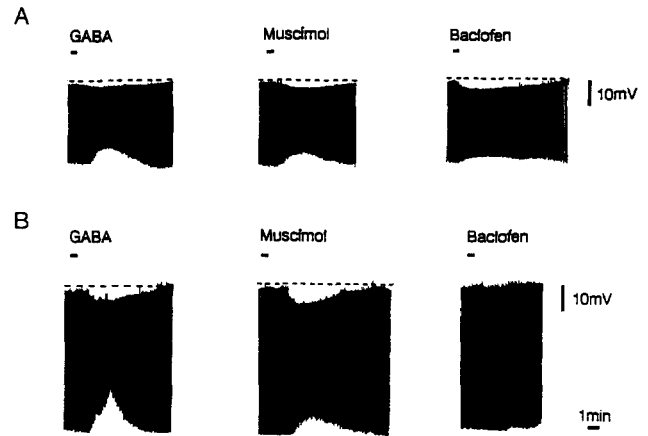
Fig. 6. A: recordings from a rNST neuron that responded to superfusion of 10^{-3} M GABA, 10^{-5} M muscimol, and 10^{-4} M baclofen. Resting membrane potential = -48 mV. B: recordings from a rNST neuron that responded to superfusion of 10^{-3} M GABA, 10^{-5} M muscimol, but did not respond to 10^{-4} M baclofen. Resting membrane potential = -52 mV.

$n = 6$) (Fig. 8b). Superfusion of the $GABA_B$ antagonist phaclofen (10^{-3} to 1.5×10^{-3} M) depressed but did not block the membrane responses to GABA in 11 neurons tested (mean reduction compared with control value for GABA = 42% ± 5.2, range 21–83%) (Fig. 8c). The effect of bicuculline on membrane responses to muscimol and baclofen was tested in 4 neurons that responded to GABA. Bicuculline totally blocked the
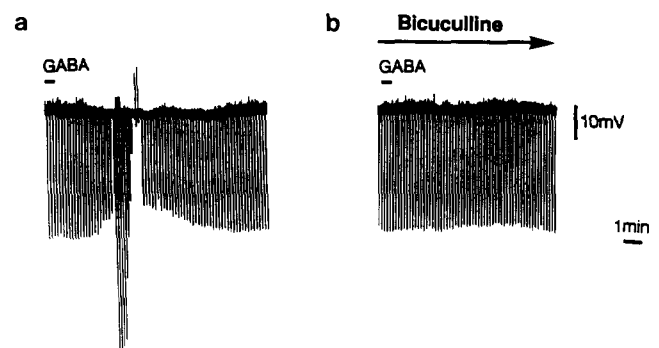
Fig. 7. Response of a rNST neuron to a application of 10^{-3} M GABA (a) alone and in the presence of 10^{-4} M bicuculline (b). Computer generated hyperpolarizing and depolarizing current pulses used to measure membrane characteristics interrupt the hyperpolarizing membrane responses in (a). Time of GABA application is indicated by the horizontal bar. Resting membrane potential = -45 mV.

Fig. 5. A–D: responses of 4 different rNST neurons to a long (1,200 ms) depolarizing current pulse alone and preceded by a short hyperpolarizing current pulse. Using this current injection protocol neurons in the rNST can be separated into 4 groups. The hyperpolarizing pulse disrupts the regular discharge pattern in Group I neurons (A), causes a long delay in Group II neurons (B) and has the least effect on Group III neurons (C). Group IV neurons respond to depolarization with a short burst of action potentials (D). Below each panel is shown the response of each of these neurons to superfusion with 10^{-3} M GABA. All of the neuron groups respond to GABA. Resting membrane potentials: A = -41 mV, B = -43 mV, C = -38 mV, D = -39 mV.
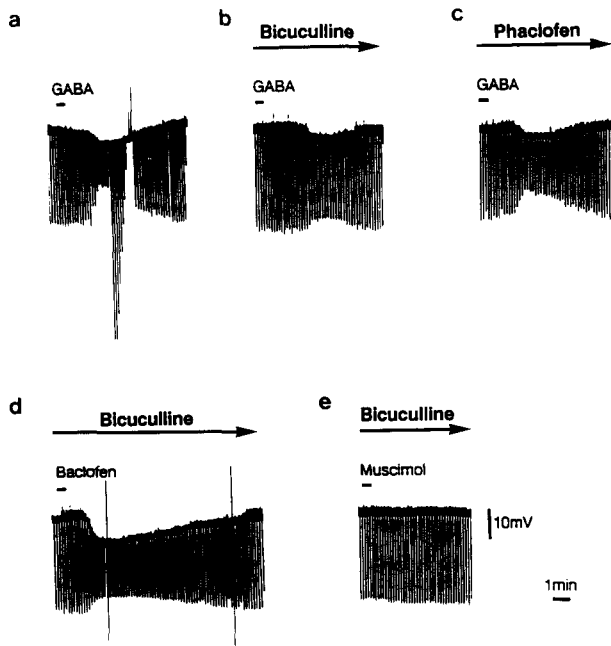
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Fig. 8. Responses of a neuron to GABA receptor agonists and antagonists. This neuron responded to (a) 10^{-3} M GABA. In the presence of 10^{-4} M bicuculline the response to GABA was partially blocked (b), the response to muscimol was totally blocked (e) and the response to baclofen was unaffected (d). In the presence of 1.5×10^{-3} M phaclofen the response to GABA was depressed (c). Computer generated hyperpolarizing and depolarizing current pulses used to measure membrane characteristics interrupt the hyperpolarizing membrane responses in traces 8a, 8d. Resting membrane potential = -47 mV.

neuronal response to muscimol (Fig. 8e) but did not antagonize responses to baclofen (Fig. 8d).

DISCUSSION

Like neurons in other parts of the central nervous system[3,43], the inhibitory neurotransmitter GABA hyperpolarizes and reduces the input resistance of neurons distributed throughout the gustatory zone of the rNST. The direct action of GABA is suggested by the persistence of its neuronal effects in the presence of TTX, or in a low Ca^{2+}, high Mg^{2+} perfusing medium, procedures known to block synaptic transmission[40,42].

There was a GABA effect in 68% of our neurons. Other investigators studying GABA rarely report neurons that do not respond to GABA. In fact it is often stated that all neurons tested respond to GABA[8,37]. Absence of a GABA response in some neurons could be due to failure of the drug to reach the neuron at sufficiently high concentrations to produce an effect. The concentrations over which GABA was effective in the present study are similar to those reported by others recording from neurons in brain slices[7], but much higher than the concentrations found effective in *isolated* NST neurons[35]. These differences in effective-

ness of GABA may be due to penetration of GABA into the slice and GABA uptake by neurons and glia; therefore, the concentration at the recording site is much lower than the applied concentration[41]. However, since GABA responsive and non-responsive neurons were situated at similar depths in the slices, failure to respond to GABA could also be due to lack of GABA receptors.

When the $GABA_A$ agonist muscimol was superfused over the slices, all neurons tested showed a reduction in input resistance accompanied by membrane hyperpolarization, suggesting that these neurons have $GABA_A$ receptors. The effects of muscimol were antagonized by bicuculline. The use of the $GABA_B$ agonist baclofen and the $GABA_B$ antagonist phaclofen demonstrated that some neurons in the rostral NST have both $GABA_A$ and $GABA_B$ receptors. The fact that some neurons did not respond to baclofen might be due to washout of cell contents during whole cell recording, potentially leading to rapid rundown of the G protein-coupled $GABA_B$ response.

That rNST neurons have both $GABA_A$ and $GABA_B$ receptors is supported by the reversal potential of the GABA effect. For most neurons the reversal potential was -60 mV, a value similar to the GABA reversal potentials measured by other investigators suggesting the involvement of Cl^- ions and $GABA_A$ receptors[12,36,37,43]. However, reversal potentials as low as -96 mV were measured for some neurons suggesting that other ions might be involved, possibly potassium ions associated with $GABA_B$ receptors.

Since most of the neurons responded to GABA, inhibition probably plays a major role in sensory processing by the rNST. Although investigators have reported that stimulation of the tongue with some taste stimuli occasionally causes inhibition of the ongoing spontaneous activity of second order neurons in the taste pathway, the predominant result of gustatory stimulation is excitation[16,39,50]. However, there is a growing body of evidence suggesting that inhibition may have a significant role in sensory processing in the rNST. Halpern and Nelson[21] recorded from a region of the gustatory NST receiving input from both the chorda tympani and glossopharyngeal nerves innervating taste receptors on the anterior and posterior tongue, respectively. When the chorda tympani nerve input was eliminated by application of local anesthesia, the response to gustatory stimulation of the posterior tongue increased in magnitude and this was interpreted as removal of an inhibitory input. Extracellular recordings from single gustatory neurons receiving convergent input from anterior tongue and posterior oral cavity taste receptors revealed that when both areas are stimulated

simultaneously, the response is not a simple summation of the neural responses to separate stimulation of anterior and posterior fields[47]. Rather, the response magnitude is between the response magnitudes evoked by stimulation of the individual fields. The weaker response seen to simultaneous stimulation of anterior or posterior receptive fields was hypothesized to be the result of inhibitory interaction.

Based on results of behavioral experiments in humans there is also evidence of inhibitory interactions between the glossopharyngeal and chorda tympani nerves at the level of the rNST. Damage or anesthesia of the chorda tympani nerve results in taste phantoms (aberrations of perceptual responses to taste stimuli) that disappear if the glossopharyngeal nerve receptive field is anesthetized[33]. Inhibitory interactions can also occur independently of convergent input derived from the chorda tympani and glossopharyngeal nerve. For example, the sodium channel blocker amiloride suppresses whole nerve and single fiber responses of the chorda tympani to NaCl[6,14,19]. When responses of the second order neurons in rNST were examined after application of amiloride to the tongue, the responses of the central neurons changed[20]. Many NST neurons increased their firing rate after the application of amiloride, which suggests that removal of the amiloride sensitive afferent input disinhibits these neurons[38]. There is also indication of a descending inhibitory influence on neurons in the rNST[23].

Anatomical evidence also suggests that GABA has an important role in the gustatory zone of the NST. Using immunocytochemical techniques, GABA-containing neurons and puncta were found in the area of termination of the chorda tympani nerve in the NST[28]. The GABAergic neurons were small, with ovoid soma, resembling Golgi type II interneurons. In a recent study in which synaptic connections onto NST projection neurons were investigated in hamster, it was found that there was a high frequency of occurence of synapses onto projection neuron soma and proximal dendrites that are possibly of the inhibitory type[54,56].

In a previous study we have shown that neurons of the rNST can be separated into 4 groups based on repetitive firing properties[5]. The neurons included in the current study were also separated into groups using similar techniques. Neurons in all groups were influenced by GABA, but not all the neurons in each group responded to GABA. Although we do not know the morphological characteristics of these neurons, we assume that our recordings probably originated from more than one morphological type. In fact, recent studies in our laboratory indicate that GABA influences projection neurons as well as local circuit neurons in the rNST in about equal proportions (King and Bradley, unpublished observations). In summary, anatomical studies, as well as electrophysiological and behavioral investigations suggest an important role for inhibition in the gustatory NST.

In the caudal NST inhibition has been shown to be important in a number of reflex functions. GABA has been localized in the caudal NST using immunocytochemical methods[15,24,30,32]. Iontophoresis[1] and microinjections[10,26,31] of GABA into the medial area of the caudal NST reduced activity in neurons receiving input from the carotid sinus and aortic nerves and caused an increase in blood pressure. Moreover, the inhibitory activity of GABA was antagonized by simultaneous injection of bicuculline[31]. Bicuculline applied alone resulted in an increase in the evoked activity of caudal NST neurons leading to the conclusion that a GABAergic inhibitory system, possibly modulated by afferent input, is functional in the caudal NST[10,31].

The involvement of GABA$_A$ receptors in the inhibitory mechanisms of the caudal NST has been examined not only by using GABA$_A$ antagonists but also by application of the GABA$_A$ agonist muscimol and nipecotic acid, a GABA uptake blocker[10]. Injection of baclofen, the GABA$_B$ agonist, was also effective in increasing blood pressure that was not blocked by GABA$_A$ antagonists. Thus, as we have observed in the rNST, both GABA$_A$ and GABA$_B$ receptors are involved in the inhibitory mechanisms of the caudal NST[9,18,46].

Other reflex mechanisms of the caudal NST involve inhibition. Investigations of the control of swallowing suggest that GABA neurons in the caudal NST exert a tonic inhibition of the medullary swallowing pattern generator[53]. Tonic GABAergic inhibition in the caudal NST has also been shown to be associated with the modulation of respiratory rhythm generation[44]. Iontophoresis of GABA and GABA$_A$ agonists and antagonists onto respiratory neurons revealed that GABA release was probably responsible for the characteristic periodic inhibition exhibited by respiratory neurons[11].

It is apparent, therefore, that GABA mediated inhibition is present throughout the rostro-caudal extent of the NST. In the caudal, visceral part of the NST, GABA is thought to tonically inhibit the nucleus. However, there is no direct evidence to indicate that the rNST is tonically inhibited.

Until recently the NST was thought to have a relatively straightforward influence on gustatory processing, primarily through excitatory synapses. When comparisons were made between the response characteristics of afferent taste fibers and second order neurons in the NST they were found to be similar[51]. There is

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evidence that convergence of afferent input occurs onto second order neurons[47,52], but it is often assumed that the afferent information is passed on relatively unchanged. However, the results of the present study suggest that inhibition plays an important role in sensory processing by rNST neurons and that afferent input can potentially be altered or modulated by inhibitory action. Moreover, not all neurons in the rNST project to rostral brain areas. Others connect locally and are involved in the control of salivation and oromotor reflexes[49]. Inhibition may play an important role in these latter functions, where afferent inputs initiate motor patterns that require inhibition as an essential part of complex muscle coordination. During processing of gustatory information, inhibitory interactions might occur to enhance certain characteristics of the sensory stimulus. These anatomical and physiological studies suggest that the rNST is a complex sensory relay nucleus processing afferent gustatory and somatosensory information involving both excitatory and inhibitory interactions.

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