Respiratory Sinus Arrhythmia
Endogenous Activation of Nicotinic Receptors Mediates Respiratory Modulation of Brainstem Cardioinhibitory Parasympathetic Neurons

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Abstract—The heart rate increases during inspiration and decreases during expiration. This respiratory sinus arrhythmia (RSA) occurs by modulation of premotor cardioinhibitory parasympathetic neuron (CPN) activity. However, RSA has not been fully characterized in rats, and despite the critical role of CPNs in the generation of RSA, little is known about the mechanisms that mediate this cardiorespiratory interaction. This study demonstrates that RSA in conscious rats is similar to that in other species. The mechanism of RSA was then examined in vitro. Rhythmic inspiratory-related activity was recorded from the hypoglossal rootlet of 700- to 800-μm medullary sections. CPNs were identified by retrograde fluorescent labeling, and neurotransmission to CPNs was examined using patch-clamp electrophysiological techniques. During inspiratory bursts, the frequency of both spontaneous γ-aminobutyric acidergic (GABAergic) and spontaneous glycinergic synaptic events in CPNs was significantly increased. Focal application of the nicotinic antagonist dihydro-β-erythroidine in an α4β2-selective concentration (3 μmol/L) abolished the respiratory-evoked increase in GABAergic frequency. In contrast, the increase in glycinergic frequency during inspiration was not altered by nicotinic antagonists. Prenatal nicotine exposure exaggerated the increase in GABAergic frequency during inspiration and enhanced GABAergic synaptic amplitude both between and during inspiratory events. Glycinergic synaptic frequency and amplitude were unchanged by prenatal nicotine exposure. This study establishes a neurochemical link between neurons essential for respiration and CPNs, reveals a functional role for endogenous acetylcholine release and the activation of nicotinic receptors in the generation of RSA, and demonstrates that this cardiorespiratory interaction is exaggerated in rats prenatally exposed to nicotine. (Circ Res. 2003;93:lll-lll.)

Key Words: nucleus ambiguus ■ vagal activity ■ respiratory sinus arrhythmia ■ prenatal nicotine ■ sudden infant death syndrome

The heart rate increases during inspiration and decreases during the postinspiration/postexpiration period. This respiratory-related change in heart rate, respiratory sinus arrhythmia (RSA), helps to match pulmonary blood flow to lung inflation and to maintain an appropriate diffusion gradient for oxygen in the lungs.1-3 RSA has been observed in neonatal4 and adult5,6 humans, baboons,7 dogs,1 rabbits,8 and seals9 but has not been well characterized in rats.

Heart rate is controlled by the activity of premotor cardioinhibitory parasympathetic neurons (CPNs) in the brainstem, and RSA is mediated in part by central respiratory modulation of CPN activity. CPNs are primarily located in the nucleus ambiguus (NA), in proximity to neurons thought to be essential for respiratory rhythmogenesis.2,3,10-13 CPNs in the NA are intrinsically silent and therefore rely on synaptic inputs to dictate their activity.14

Although the pathways and transmitters responsible for respiratory modulation of CPNs are unknown, γ-aminobutyric acid (GABA), glycine, and acetylcholine (ACh) are all neurotransmitters that have been implicated in the central generation of RSA. CPNs are inhibited during inspiration, and this inhibition has been reversed by the intracellular injection of CI− (Gilbey et al15). This suggests that GABA- and/or glycine-mediated chloride channels may be involved in respiratory modulation of CPNs. Paradoxically, however, one author of the Gilbey et al study described in a later review that the inhibition of CPNs during inspiration could not be inhibited by the GABA A antagonist bicuculline or the glycine antagonist strychnine.2

ACh has been shown to inhibit CPN activity,15 and recent work has shown that endogenous ACh activates presynaptic nicotinic receptors, which enhance both GABAergic and glycinergic inputs to CPNs.16 The possible involvement of nicotinic receptors in mediating RSA is interesting because prenatal nicotine augments parasympathetic and reduces sympathetic control of the heart rate17 and is among the highest risk factors for sudden infant death syndrome (SIDS).18,19 Infants that succumb to SIDS often experience a
sustained bradycardia, which is preceded or accompanied by a life-threatening apnea.19,20 These life-threatening events in SIDS victims are thought to be caused by exaggerated central cardiorespiratory interactions.17,19

The aim of the present study was to test whether rats have an RSA pattern similar to that of other species and to elucidate the cellular mechanisms responsible for the respiratory modulation of CPNs. Specifically, we tested the hypothesis that heart rate increases during inspiration in rats. In addition, we tested whether CPNs receive increased GABAergic and glycinegic synaptic inputs during inspiratory-related activity. Furthermore, we examined whether the respiratory modulation of CPNs is dependent on endogenous activation of nicotinic receptors. Because our work demonstrates that endogenous activation of nicotinic receptors is responsible for RSA, we tested whether prenatal nicotine exposure alters these cardiorespiratory interactions.

Materials and Methods

Plethysmographic/Blood Pressure Recordings

Adult female Sprague-Dawley rats (85-155 g, Hilltop, Scottdale, Pa) were initially exposed to isoflurane (Abbott Laboratories) until anesthetized and cooled to ~4°C. A right thoracotomy was performed, and the retrograde fluorescent tracer X-rhodamine-5- and 6-isoisothiocyanate (Molecular Probes) was injected into the fat pads at the base of the heart. After 24 hours of recovery, each animal was anesthetized with isoflurane and decapitated, and the heart was placed in a 4°C physiological saline solution (mmol/L: NaCl 140, KCl 5, CaCl2 2, glucose 5, and HEPES 10, pH 7.4). All animal procedures were performed with the approval of the Animal Care and Use Committee of The George Washington University in accordance with the recommendations of the panel on euthanasia of the American Veterinary Medical Association and the National Institutes of Health publication Guide for the Care and Use of Laboratory Animals. The medulla was removed with care to preserve the hypoglossal cranial nerve rootlet. The medulla was mounted on a cutting block and placed into a vibrating blade microtome (Leica). Serial transverse sections were sliced in a rostrocaudal progression until the inferior olives and the NA could be visualized on the rostral surface of the tissue. A single thick (700- to 800-μm) section that included CPNs, the hypoglossal nerve rootlet, the pre-Botzinger complex, and the rostral portion of the hypoglossal nucleus was cut and transferred to a recording chamber and perfused (4 mL/min) with room temperature aCSF (mmol/L: NaCl 125, KCl 3, CaCl2, 2, NaHCO3, 26, glucose 5, and HEPES 5) equilibrated with 95% O2/5% CO2, pH 7.4.

Recording Respiratory Network Activity

The thick medullary slice preparation contains the pre-Botzinger complex, local circuits for motor output generation, and respiratory hypoglossal motor neurons, which generate inspiratory-phase motor discharge in hypoglossal cranial nerves.13 As seen in other similar medullary respiratory slice preparations, the frequency of respiratory-related hypoglossal discharge is significantly lower than that in in vivo preparations; this is likely due to the reduced temperature of the preparation and the absence of sensory input to the medulla.21 Spontaneous respiratory-related activity was recorded by monitoring the motor neuron population activity from hypoglossal nerve rootlets using a suction electrode. Hypoglossal rootlet activity was amplified (50,000 times), filtered (10- to 300-Hz bandpass, CWE Inc), and adjacent-averaged (50-ms windows). Respiratory activity was also electronically integrated (τ=50 ms, CWE Inc) during experiments examining glycinegic synaptic inputs to CPNs.

Patch-Clamp Techniques

CPNs in the NA were identified by the presence of the fluorescent tracer.22 Patch pipettes (2.5 to 3.5 MΩ) were visually guided to the surface of individual CPNs using differential interference optics and infrared illumination (Zeiss). Patch pipettes contained (mmol/L) KCl 150, MgCl2 4, EGTA 2, Na-ATP 2, and HEPES 10, pH 7.4. This pipette solution causes the Cl− current induced by the activation of GABA or glycine receptors to be recorded as an inward current (calculated reversal potential of Cl−: −4 mV). Voltagle-clamp recordings were made with an Axopatch 200B and pClamp 8 software (Axon Instruments). All synaptic activity in CPNs was recorded at −80 mV. Only preparations in which synaptic activity increased in CPNs during inspiration (in 95 of 117 [81%] of the preparations) were used for further experimentation and analysis. Only one cell was recorded per nucleus for an experiment. In 12 slices, an additional cell was recorded from the same slice in the contralateral NA.

Focal Drug Application

Focal drug application was performed using a pneumatic Picopump pressure delivery system (WPI). Drugs were ejected from a patch pipette positioned within 30 μm from the patched CPN. The maximum range of drug application has been previously determined to be 100 to 120 μm downstream from the drug pipette.23 GABAergic neurotransmission was isolated by focal application of d-2-amino-5-phosphonovalerate (AP-5, 50 μmol/L), 6-cyano-7-nitroquinoxaline-2,3-dione (CNQX, 50 μmol/L), and strychnine (1 mmol/L) to block N-methyl-D-aspartate (NMDA), non-NMDA, and glycinegic receptors, respectively. Glycinegic neurotransmission was isolated by focal application of AP-5, CNQX, and gabazine (25 μmol/L) to block NMDA, non-NMDA, and GABAA receptors, respectively. Nicotinic receptors were blocked with dihydro-β-erythroidine (DHβE, 100 μmol/L) or curare (10 μmol/L). The role of different receptor subtypes was tested by applying DHβE at concentration selective for the α3β2 nicotinic receptor (3 μmol/L).24 Nicotinic receptor subtypes were tested with the α7 nicotinic receptor agonist α7-bungarotoxin (α-BTX, 100 nmol/L). All drugs were obtained from Sigma.

Prenatal Nicotine Exposure

Adult female rats were anesthetized with ketamine (40 mg/kg)/xylazine (5 mg/kg IP, Phoenix Pharmaceuticals) on the third day of gestation and implanted with Alzet osmotic minipumps (Durect) containing (−)-nicotine (56.1 mg/mL bacteriostatic saline, Sigma). Osmotic minipumps were chosen to avoid the high plasma nicotine concentrations and subsequent episodic fetal hypoxia/schemia that can be produced by nicotine injections.25 Pumps delivered 2.1 mg nicotine per day, a level approximately equivalent to levels that occur in moderate to heavy smokers, for 28 days.17

Data Analysis

Plethysmographic/Blood Pressure Experiments

Heart rate intervals were measured during inspiratory and subsequent expiratory periods in 6 animals using AcqKnowledge (version 3.7.3, Ace...
Biopac Systems). Heart rate was recorded from at least 20 respiratory cycles while the animal was awake and sedentary. Data are presented as mean±SEM. Statistical comparisons were made using paired Student t tests. A value of *P*<0.05 indicates significant differences.

**Electrophysiology**

Synaptic events were detected using MiniAnalysis (version 5.6.12, Synaptosoft). The frequency and amplitude of inhibitory postsynaptic currents (IPSCs) that occurred in CPNs during inspiratory-related hypoglossal activity were averaged to determine inspiratory values. Control values were determined by averaging IPSCs that occurred in a 5- to 10-second window ending 1 second before inspiratory burst onset and beginning at least 3 seconds after the end of any previous inspiratory activity. All data are presented as mean±SEM. Statistical comparisons were made using paired or unpaired Student t tests, as appropriate. A value of *P*<0.05 indicates significant differences.

**Results**

**Sprague-Dawley Rats Exhibit RSA Pattern Similar to That of Other Species**

Respiratory airflow (Figure 1, top) and blood pressure (Figure 1, bottom) were simultaneously recorded in 6 conscious, freely moving rats. During inspiration, the average heartbeat interval decreased significantly from 171±4 ms during expiration to 167±4 ms during inspiration (*P*<0.05). This change in heart period corresponds to an average inspiratory-related increase in heart rate of 6.9±1.9 bpm (*P*<0.05).

**CPNs Are Inhibited During Inspiration by Endogenous Nicotinic ACh Receptor–Mediated Increases in GABAergic Activity**

To determine the cellular basis of RSA, the synaptic activity of CPNs was measured in vitro. GABAergic neurotransmission was isolated by focal application of the glutamatergic and glycinergic antagonists AP-5, CNQX, and strychnine in 22 cells (from 17 preparations). The focal application of these antagonists did not significantly alter the frequency (*P*>0.05) or duration (*P*>0.05) of the respiratory activity. During inspiration, the frequency of GABAergic synaptic inputs to CPNs was significantly increased (basal 5.2±0.7 Hz, inspiration 10.5±1.3 Hz, *P*<0.01, *n*=22 cells; Figure 2a). All IPSCs under these recording conditions were blocked by focal application of the GABAA antagonist gabazine (Figure 2b). Focal application of the nicotinic antagonist curare significantly reduced the inspiratory-related increase in GABAergic synaptic frequency (control basal 8.5±1.3 Hz, curare basal 2.6±0.4 Hz, *P*<0.05, *n*=12 cells from 10 preparations; Figure 2c) but did not significantly affect the basal frequency of IPSCs between bursts (*P*>0.05, *n*=12 cells). GABAergic synaptic amplitude was not significantly altered by inspiratory activity or by the application of curare (*P*>0.05, *n*=12 cells).

**Determination of the nAChR Subtype Mediating Inspiratory-Related Increase in GABAergic Input to CPNs**

To determine the specific nicotinic ACh receptor (nAChR) subtype mediating the respiratory-related increase in GABAergic frequency, subtype-selective nicotinic antagonists were used. Focal application of αBTX (α4-selective nicotinic antagonist) had no significant effect on the frequency of GABAergic synaptic inputs to CPNs between inspiratory bursts (control 4.9±1.2 Hz, αBTX 5.5±1.2 Hz, *P*>0.05, *n*=4 cells) and did not alter the inspiratory-related increase in GABAergic synaptic frequency (control basal 5.0±1.2 Hz, control inspiration 15.2±2.7 Hz, αBTX basal 5.7±1.1 Hz, αBTX inspiration 11.4±2.4, *P*>0.05, *n*=4 cells from 4 preparations). Focal application of the nicotinic antagonist DHβE, in a concentration selective for the αβ3 receptor subtype (3 μmol/L), did not affect GABAergic synaptic frequency between bursts (control 8.5±1.7 Hz, DHβE 6.4±1.2 Hz, *P*>0.05, *n*=6 cells from 3 preparations) but did abolish the increase in GABAergic frequency during inspiration (control basal 8.5±1.7 Hz, control inspiration 13.9±2.7 Hz, DHβE control 6.4±1.2 Hz, DHβE inspiration...
GABAergic synaptic amplitude was not significantly altered by αBTX (control 49.7±8.2 pA, αBTX 40.5±8.9 pA, P>0.05, n=4 cells) or DHβE (control 57.2±11.4 pA, DHβE 52.9±9.2 pA, P>0.05, n=6 cells).

**Glycinergic Respiratory Inputs to CPNs**

In an additional 13 cells (from 10 preparations), glycinergic activity was isolated by focal application of the glutamatergic and GABAergic antagonists AP-5 (50 μmol/L), CNQX (50 μmol/L), and strychnine (1 mmol/L), respectively. During inspiratory activity, the frequency of GABAergic IPSCs in CPNs was significantly increased (P<0.05). GABAA antagonist gabazine blocked all IPSCs. Nicotinic receptor antagonist curare (10 μmol/L) significantly inhibited (P<0.05) the inspiratory-related increase in GABAergic synaptic frequency in CPNs. Representative traces in panels a, b, and c are from 3 CPNs.

**Effect of Prenatal Nicotine Exposure on GABAergic and Glycinergic Synaptic Inputs to CPNs**

**GABA**

The frequency of GABAergic synaptic events increased 460±90% in animals prenatally exposed to nicotine (n=18

8.2±1.8 Hz, P<0.05, n=6 cells; Figure 3). GABAergic synaptic amplitude was not significantly altered by αBTX (control 49.7±8.2 pA, αBTX 40.5±8.9 pA, P>0.05, n=4 cells) or DHβE (control 57.2±11.4 pA, DHβE 52.9±9.2 pA, P>0.05, n=6 cells).

**Glycinergic Respiratory Inputs to CPNs**

In an additional 13 cells (from 10 preparations), glycinergic activity was isolated by focal application of the glutamatergic and GABAergic antagonists AP-5, CNQX, and gabazine. The application of these antagonists did not significantly alter the frequency (P>0.05) or duration (P>0.05) of the respiratory activity. During inspiration, glycinergic synaptic frequency was also significantly increased (basal 11.0±2.2 Hz, inspiration 19.0±3.5 Hz, P<0.01, n=13 cells; Figure 4a). Focal application of the nicotinic antagonist DHβE in a high concentration that blocks all nicotinic receptors (100 μmol/L, Figures 4b, 4c, and 4f) did not significantly alter the inspiratory-related increase in glycinergic frequency (control basal 13.4±3.8 Hz, control inspiration 22.3±6.3 Hz, DHβE 13.4±4.0 to 22.0±6.1 Hz, P>0.05, n=7 cells from 5 preparations). DHβE did not significantly alter the frequency of glycinergic synaptic events between inspiratory events (DHβE, n=7 cells, P>0.05). All IPSCs under these recording conditions were reversibly blocked by focal application of strychnine (Figures 4d through 4f). Glycinergic amplitude was not altered by respiratory activity (basal 52.0±5.1 pA, inspiration 59.6±9.1 pA, P>0.05, n=13 cells) or by application of DHβE (control 52.0±5.1 pA, DHβE 44.9±7.7 pA, P>0.05, n=7 cells). Application of 100 μmol/L DHβE did not significantly alter the frequency (P>0.05) or duration (P>0.05) of the respiratory activity.
cells from 17 preparations), a significant exaggeration of the 260±40% increase observed in unexposed animals (n=22 cells, P<0.01; Figures 5a through 5c and 5e). Prenatal nicotine did not significantly alter the frequency of GABAergic synaptic events between inspiratory bursts (unexposed 5.2±0.7 Hz [n=22 cells], prenatal nicotine 7.7±0.7 [n=18 cells], P>0.05). Focal application of DHβE at a concentration (3 μmol/L) selective for the α4β2 receptor subtype (3 μmol/L) did not significantly change GABA synaptic frequency between bursts. c and d, Gabazine (25 μmol/L) reversibly blocked all IPSCs under these recording conditions. Representative traces in panels a through d are from the same CPN. e, Values are mean±SEM from 6 cells. *P<0.05 and **P<0.01.

Discussion
There are four major findings from the present study: (1) Heart rate increases during inspiration and decreases during expiration in conscious, unrestrained rats. (2) CPNs in the brainstem are inhibited during inspiration by an increase in both GABAergic and glycinergic synaptic inputs. (3) The respiratory-related increase in GABAergic activity, but not glycinergic activity, is mediated by the endogenous activation of α4β2 nicotinic ACh receptors. (4) Prenatal nicotine exposure significantly exaggerates the GABA-mediated, but not glycine-mediated, inhibition of CPNs during inspiration.

RSA Pattern in Rats
It is well established in many species (including neonatal4 and adult5,6 humans, baboons,7 dogs,8 seals,9 and rabbits8) that the heart rate increases during inspiration and decreases
during inspiration. This RSA improves the efficiency of pulmonary gas exchange by better matching ventilation and pulmonary blood flow.\(^1,2,9\) This inspiratory-related tachycardia is predominantly mediated by a reduction in cardiac vagal activity due to the decreased activity of CPNs in the NA.\(^2,3,8,15,27–30\) However, data describing cardiorespiratory interactions in the rat are contradictory. A recent in vivo study has paradoxically shown that in contrast to all other studied species, the activity of CPNs is enhanced during inspiration in rats.\(^31\) However, there are several factors that make the results from that study difficult to interpret. These include a desynchronization of central respiratory activity from lung inflation and using anesthetics, which in general reduce or eliminate parasympathetic cardiac activity. In contrast, a recent study using the rat working heart brainstem preparation (a preparation without anesthetics) demonstrates that heart rate increases during inspiration, consistent with a study in other species.\(^32\) The results from the present study unequivocally demonstrate that similar to the RSA that occurs in other species, heart rate increases during inspiration in conscious, freely moving rats.

**Inhibitory Respiratory-Related Synaptic Inputs to CPNs**

Previous in vivo work has shown that CPNs are inhibited during inspiration via a chloride-mediated current.\(^15\) The present study demonstrates that CPNs receive an increased frequency of both GABAergic and glycinergic IPSCs during inspiration. This respiratory-dependent inhibition of CPN activity provides a cellular mechanism for the tachycardia that occurs during the inspiratory phase of the respiratory cycle.
Involvement of Nicotinic Receptors in RSA

The GABA-mediated inhibition of CPNs during inspiration was significantly inhibited by curare, indicating that the increase in GABAergic frequency is mediated by the activation of nicotinic receptors. Further investigation revealed that this increase in GABAergic frequency was unaffected by α-BTX, demonstrating that it was not mediated by the activation of the α7 nAChR subtype. However, an α4β2-selective concentration of DHβE abolished the GABAergic inhibition of CPNs during inspiration, demonstrating that activation of α4β2 nAChRs by endogenous ACh is essential for the GABAergic component of this cardiorespiratory interaction. The facilitation of GABAergic inputs to CPNs by activation of nicotinic receptors is consistent with previous work, which has shown that spontaneous GABAergic synaptic inputs to CPNs are enhanced by the activation of α4β2 receptors located in the presynaptic terminals of GABAergic neurons. The present study also indicates that the nicotinic receptors responsible for the increased GABAergic activity during inspiration are in proximity to the CPNs, inasmuch as the focal application of the nicotinic antagonist DHβE abolished this increase.

In contrast, greater (100 μmol/L) concentrations of DHβE did not significantly alter the respiratory-related increase in glycinergic synaptic frequency in CPNs. Interestingly, previous studies have shown that spontaneous glycinergic inputs to CPNs are also enhanced by the activation of α4β2 nicotinic receptors in glycinergic presynaptic terminals. This suggests that although glycinergic inputs to CPNs possess presynaptic nicotinic receptors, the respiratory-evoked increase in glycinergic synaptic input to CPNs is not mediated by the activation of nicotinic receptors. Alternatively, there may be nicotinic modulation of glycinergic activity that occurs at a location distant from the CPNs and out of the range of the focal application of drugs in the present study.

Prenatal Nicotine Exposure and Respiratory-Related Synaptic Inputs to CPNs

In animals prenatally exposed to nicotine, the inspiratory-related increase in GABAergic, but not glycinergic, synaptic inputs to CPNs. a, In animals prenatally exposed to nicotine, CPNs received increased GABAergic synaptic input during inspiration. b, In unexposed animals, the frequency of GABAergic IPSCs increased 260±90% during inspiration. In animals prenatally exposed to nicotine, the frequency of GABAergic IPSCs increased 460±40% during inspiration, which is a significant augmentation (P<0.05) of this response. Representative traces in panels a and b are from 3 CPNs. c, Values are mean±SEM from 22 control and 18 prenatal nicotine experiments. **P<0.01. d, GABAergic IPSC amplitude is significantly increased by prenatal nicotine exposure both between and during inspiratory bursts. Unexp indicates the group not exposed to nicotine; Pre Nic, the group exposed to prenatal nicotine. Values are mean±SEM from 22 control and 18 prenatal nicotine experiments. *P<0.05. e, Values are mean±SEM percent increase of the inspiratory-related increase in GABAergic (n=22 Unexp cells, n=18 Pre Nic cells) and glycinergic (n=13 Unexp cells, n=11 Pre Nic cells) IPSCs in CPNs during inspiration. **P<0.05. Prenatal nicotine exposure significantly exaggerates the inspiratory-related increase in GABA frequency. In contrast, the inspiratory-related increase in glycinergic frequency is not significantly altered by prenatal nicotine exposure.
twice that of unexposed animals, whereas the inspiratory-dependent increase in glycinergic frequency was not significantly different in control and nicotine-exposed animals. This is consistent with the results that nicotinic antagonists abolished the inspiratory-related increase in GABAergic frequency to CPNs but did not alter the respiratory modulation of glycinergic IPSCs to CPNs. In addition to enhancing the increase in frequency of GABAergic synaptic inputs to CPNs during inspiration, prenatal nicotine exposure also caused a significant increase in the amplitude of both spontaneous and inspiratory-evoked GABAergic synaptic inputs to CPNs.

Other studies have shown that the $\alpha_2\beta_2$ nAChR subtype is significantly upregulated in rat brains chronically exposed to nicotine and that $\alpha_2\beta_2$ receptors chronically exposed to nicotine exhibit enhanced responses to ACh and are less sensitive to desensitization. A greater number of, enhanced responses to, and reduced desensitization of $\alpha_2\beta_2$ nicotinic receptors may be responsible for the prenatal nicotine-induced exaggeration of the $\alpha_2\beta_2$-mediated increase in GABAergic synaptic frequency in CPNs during inspiration.

The $\alpha_2\beta_2$ receptor antagonist DHβE (3 μmol/L) significantly inhibited the inspiratory-related increase in GABAergic frequency in animals prenatally exposed to nicotine, indicating that activation of $\alpha_2\beta_2$ nicotinic receptors by endogenous ACh also mediates this cardiorespiratory interaction in animals prenatally exposed to nicotine. In addition, $\alpha_2\beta_2$ block significantly reduced the frequency of spontaneous, non–inspiratory-related GABAergic synaptic inputs to CPNs in animals prenatally exposed to nicotine but not in unexposed animals. This suggests that prenatal nicotine augments endogenous cholinergic control of GABAergic inputs to CPNs in animals prenatally exposed to nicotine.

These alterations in cardiorespiratory control with prenatal nicotine exposure may be clinically important. Maternal cigarette smoking is highly correlated with SIDS, and it has been suggested that SIDS is caused by an alteration of brainstem sites responsible for cardiorespiratory control. Infants that subsequently succumb to SIDS have heart rates higher than those in other infants. The exaggerated amplitude of all GABAergic inputs to CPNs and enhanced increase in GABAergic synaptic frequency during inspiration observed the present study would be expected to evoke an elevated basal heart rate and a greater than normal tachycardia during inspiration. This nicotine-mediated facilitation of GABAergic neurotransmission to CPNs provides possible mechanisms for the elevated heart rate in SIDS victims and the elevated heart rate prevalent in smokers.

In summary, rats possess normal RSA, and CPNs are inhibited during inspiration by an increase in the frequency of both GABAergic and glycinergic synaptic inputs. The inspiratory-related increase in GABAergic synaptic frequency is mediated by the activation of $\alpha_2\beta_2$ nAChRs and is significantly exaggerated by prenatal exposure to nicotine. These data show a neurochemical link between the neurons essential for respiration and neurons that control heart rate and reveal a physiological role of endogenous ACh release and the activation of nicotinic receptors in the generation of RSA.

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References