Serotonergic projection from nucleus raphe pallidus to rostral ventrolateral medulla modulates cardiovascular reflex responses during acupuncture


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Moazzami A, Tjen-A-Looi SC, Guo Z, Longhurst JC. Serotonergic projection from nucleus raphe pallidus to rostral ventrolateral medulla modulates cardiovascular reflex responses during acupuncture. J Appl Physiol 108: 1336–1346, 2010. First published February 4, 2010; doi:10.1152/japplphysiol.00477.2009.—We have demonstrated that stimulation of somatic afferents during electroacupuncture (EA) inhibits sympathoexcitatory cardiovascular rostral ventrolateral medulla (rVLM) neurons and reflex responses. Furthermore, EA at P5-P6 acupoints over the median nerve on the forelimb activates serotonin (5-HT)-containing neurons in the nucleus raphe pallidus (NRP). The present study, therefore, examined the role of the NRP and its synaptic input to neurons in the rVLM during the modulatory influence of EA. Since serotonergic neurons in the NRP project to the rVLM, we hypothesized that the NRP facilitates EA inhibition of the cardiovascular sympathoexcitatory reflex response through activation of 5-HT1A receptors in the rVLM. Animals were anesthetized and ventilated, and heart rate and blood pressure were monitored. We then inserted microinjection and recording electrodes in the rVLM and NRP. Application of bradykinin (10 μg/ml) on the gallbladder every 60–90 min induced consistent excitatory cardiovascular reflex responses. Stimulation with EA at P5-P6 acupoints reduced the increase in blood pressure from 41 ± 4 to 22 ± 4 mmHg for more than 70 min. Inactivation of NRP with 50 nl of kainic acid (1 mM) reversed the EA-related inhibition of the cardiovascular reflex response. Similarly, blockade of 5-HT1A receptors with the antagonist WAY-100635 (1 mM, 75 nl) microinjected into the rVLM reversed the EA-evoked inhibition. In the absence of EA, NRP microinjection of dl-homocysteic acid (4 mM, 50 nl), to mimic EA, reduced the cardiovascular and rVLM neuronal excitatory reflex response during stimulation of the gallbladder and splanchnic nerve, respectively. Blockade of 5-HT1A receptors in the rVLM reversed the NRP dl-homocysteic acid inhibition of the cardiovascular and neuronal reflex responses. Thus activation of the NRP, through a mechanism involving serotonergic neurons and 5-HT1A receptors in the rVLM during somatic stimulation with EA, attenuates sympathoexcitatory cardiovascular reflexes.

FOR MANY YEARS, ACUPUNCTURE and, more recently, electroacupuncture (EA) have been used to treat a number of diseases, including myocardial ischemia, arrhythmias, and hypertension (24, 32, 34, 43). Acupuncture or EA applied at Neiguan-Jianshi acupoints (P5–P6) of the pericardial meridian, through stimulation of the median nerve in the wrist, significantly modulates cardiovascular function (7, 8, 18). More specifically, EA stimulation at P5-P6 acupoints with low current and low frequency (2–4 mA, 2 Hz, 0.5 ms) reduces the extent of myocardial ischemia in response to an imbalance between oxygen supply and demand during reflex autonomic stimulation (18).

The rostral ventrolateral medulla (rVLM) is an important medullary region that participates in the modulation of sympathoexcitatory cardiovascular reflex responses by EA (19, 36, 37). Opioid μ- and δ-receptors, as well as nociceptin and γ-aminobutyric acid (GABA) in rVLM, play an important role during the immediate EA-inhibitory influence on the sympathoexcitatory cardiovascular reflex response (10, 19, 35).

In addition to its immediate effects, acupuncture has the ability to cause prolonged modulation of cardiovascular excitatory reflexes for as long as 10–12 h in unanesthetized animals (42). In this regard, in a series of investigations, we have examined a long-loop pathway and the neurochemicals involved in the underlying mechanisms of the EA-related inhibitory influences on the cardiovascular responses, lasting for 60–90 min in unanesthetized animals. We have identified that the hypothalamic arcuate nucleus, mesencephalic ventrolateral periaqueductal gray (vIPAG), and rVLM are important regions involved in the neuronal circuitry (20, 22, 23, 38). GABA and opioids, but not nociceptin, are involved in the prolonged cardiovascular effects of EA (35). The current study explores an additional medullary region, the nucleus raphe pallidus (NRP) and contributing neurotransmitters.

The medullary midline or raphe nuclei, through their influence on neurons in caudal and rostral VLM, modulate sympathoexcitatory outflow and cardiovascular responses (9, 40). The raphe, specifically the NRP, the most ventral subdivision of the raphe, contains serotonergic neurons that project to the rVLM (3). Involvement of raphe nuclei and their projections to the rVLM in EA-mediated modulation of the cardiovascular reflex responses have not been evaluated. Our previous anatomical data have shown that serotonin-containing neurons in the NRP may contribute to the EA cardiovascular response (14). Serotonin1A or 5-hydroxytryptamine (5-HT1A) receptors in the rVLM contribute to sympathoinhibition of cardiovascular responses to severe hemorrhage and inhibit somatosympathetic cardiovascular reflexes (12, 27). We, therefore, hypothesized that a serotonin projection from the NRP to the rVLM through a 5-HT1A mechanism participates in the EA inhibition of cardiovascular sympathoexcitatory reflex responses. These data have been published in preliminary form (28).

MATERIALS AND METHODS

Surgical Procedures

The animal use and care committee at the University of California, Irvine, approved all surgical and experimental protocols of this study. All procedures were carried out in accordance with the US Society for Neuroscience and the National Institutes of Health guidelines. The

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minimal possible number of cats was used to obtain reproducible and statistically significant results. Cats of both sexes were anesthetized initially with an injection of ketamine (40 mg/kg im). The femoral vein and artery were cannulated for administration of drugs and fluids and measurement of arterial blood pressure (Statham P 23 ID, Oxnard, CA), respectively. An intravenous injection of α-chloralose (50 mg/kg iv) was administered. Supplemental α-chloralose (5–10 mg/kg iv) was given, if the animals exhibited a corneal reflex, withdrew a limb in response to a noxious stimulus during the experiment, or displayed an unstable respiratory pattern or blood pressure. Heart rate (HR) was derived from the arterial pressure pulse by a biotech (Gould Instrument, Cleveland, OH). Intubation of the trachea facilitated artificial respiration (Harvard pump, model 662, Ealing, South Natick, MA). Arterial blood gases were examined frequently (Radiometer, Model ABL-3, Westlake, OH) and were maintained within the normal physiological range (P_{O2}, 100–150 Torr; P_{CO2}, 28–35 Torr; pH 7.35–7.45) by intravenous administration of 8% sodium bicarbonate or by adjusting the ventilator. Body temperature was kept between 36 and 38°C, using a water-perfused heating pad and an external heat lamp, as needed.

A right lateral laparotomy was performed to expose the surface of the gallbladder and to isolate the splanchnic nerve. This allowed direct placement of a bradykinin (BK) presoaked pledget on the serosal surface of the gallbladder. To quantify neuronal activity in the rVLM, we placed a bipolar flexible platinum stimulating electrode around the surface of the gallbladder and to isolate the splanchnic nerve. This allowed direct application of the rVLM electrode or a three-barrel pipette rostro-ventrally advanced ventrally 4.8 mm to reach the NRP. Alternatively, in experiments in which a closely located rVLM electrode was used (see below), the NRP electrode was positioned at the obex and advanced rostro-ventrally ~6 mm at a 53° angle to the dorsal surface of the medulla. We positioned the rVLM electrode or a three-barrel pipette perpendicularly to the dorsal surface of the medulla using visual approximation, 3–3.5 mm laterally and 3–3.5 mm rostrally relative to the obex, and it was advanced 5 mm ventrally. At the end of the experiment, the recording and microinjection sites were marked with Chicago blue dye for later histological confirmation following administration of drugs into the NRP and rVLM. Acupuncture needles were inserted to a depth of ~4 mm, bilaterally, at the Neiguan-Jianshi acupoints (PS5-P6). Needles at these acupoints were located 2–3 cm proximal to the flexor crease on the wrist and were separated by 5–7 mm. They were connected to an isolation unit and stimulator (Grass, model S88) to deliver bipolar stimuli.

**Methods of Blockade**

The role of serotonin in the rVLM during EA was evaluated by microinjection of the 5-HT_{1A} receptor antagonist WAY-100635 (1 mM, 50–75 nl, Research Biochemical International) 20 min after stimulation was terminated. Saline served as the control.

The importance of the NRP in the acupuncture response was determined by microinjection of kainic acid (KA; 1 mM, 50 nl) into the midline medullary region. Thus, either 50 nl of KA or its vehicle control, 0.9% saline, was injected into the NRP after termination of stimulation at a time when the cardiovascular effects of EA were still present.

To demonstrate an inhibitory role of the serotonergic projection from the NRP to the rVLM during sympathoexcitatory cardiovascular response, the NRP was activated by microinjection of dl-homocysteic acid (DLH, 4 mM, 50 nl), to mimic EA, while the 5-HT_{1A} receptors in the rVLM were blocked with WAY-100635. In addition, to confirm the NRP-rVLM projection, we recorded splanchnic nerve-evoked rVLM extracellular neuronal activity in response to microinjection of DLH in the NRP before and after iontophoresis of the 5-HT_{1A} receptor antagonist in the rVLM. Iontophoresis using a Neuro Phore BH-2 system (Medical System, Greenvale, NY) with saline vehicle or WAY-100635 before a third DLH-NRP microinjection lasted for 2 min. A current of 120–130 nA was used for iontophoresis.

**Stimulating and Recording Methods**

Repeated stimulation every 10 min of the gallbladder with BK (10 μg/ml) or splanchnic nerve (2 Hz, 0.4–0.6 mA; 0.5 ms) induced consistent increases in blood pressure or neuronal rVLM activity (35). The median nerves beneath the acupoints PS5-P6 were stimulated bilaterally with EA at 2–4 Hz, 2–4 mA, using a 0.5-ms pulse (38). Previous study has shown that these stimulation parameters applied at PS5-P6 activate both group III and IV afferents in the median nerve to decrease sympathoexcitatory cardiovascular responses (18, 39). We applied 30 min of EA to simulate clinical use of this procedure. The intermedio-lateral (IML) column at T_{3–7} was stimulated electrically with 0.1–0.4 mA, 2 Hz, and 0.5 ms to induce antidromic stimulation and to test for collision (20, 35–37). The location of the IML was determined preliminarily during the experiment with electrical stimulation (10–40 μA), which evoked a small, reproducible excitatory response of 5–10 mmHg and confirmed anatomically after the experiment.

**RSN recording.** A subgroup of rVLM neurons was characterized as presympathetic by demonstrating a relationship between rVLM discharge and renal sympathetic activity. To record renal nerve activity, a recording electrode placed around the renal nerve was attached to a high-impedance probe (model HIP511), and the signal was amplified (Grass P511), monitored with an oscilloscope (model 2201, Tektronix, Beaverton, OR), and processed with a Pentium IV computer for offline analysis through an analog-to-digital converter CED micro1401 MK II interface system. A window discriminator was set with a threshold above the noise level to assess renal nerve discharge activity (20).

**Extracellular rVLM recordings.** Single-unit activity of rVLM neurons was recorded with a platinum electrode inserted in a three-barrel pipette positioned in the rVLM. Action potentials were amplified with a preamplifier (Grass P511) attached to a high-impedance probe (Grass H1P5) and then filtered (0.3–10 kHz) and monitored with an oscilloscope (Tektronix 2201). Renal nerve activity, rVLM action potentials, blood pressure, and HR were digitized with a data-acquisition CED micro1401 MK II interface system. Data were analyzed offline with a Pentium IV computer and CED Spike 2 Windows.
software. Rectified and nonrectified action potentials were analyzed both visually and with the Spike 2 program using wave shape recognition algorithms to allow detection of similar wave shapes, heights, and latencies of response. Peristimulus time histograms were constructed for each neuron to assess evoked responses to stimulation of splanchnic or median nerves. Relationships between rVLM neuronal activity and blood pressure or renal nerve activity were assessed by both time and frequency domain analyses using arterial pulse and spike-triggered averaging and coherence analysis (20, 35). Examination for baroreceptor afferent input with either nitroglycerin (2.5 mg/ml) or phenylephrine (2 mg/ml) provided additional characterization of rVLM neurons.

Retrograde Tracing and c-Fos Staining: Microinjection of a Retrograde Tracer into Rat rVLM

To anatomically examine for a direct projection between the NRP and rVLM that might be involved in EA-mediated inhibition, using stereotaxic positioning to guide placement of the tip of the injection pipette in the medulla in the region of the rVLM, we microinjected a retrograde tracer in rats (350–500 g), as we have described previously (20). A mixture of ketamine-xylazine (80:12 mg/ml, Sigma) was used to induce (0.3–0.4 ml im) and maintain (0.1–0.2 ml im) anesthesia. Body temperature was monitored with a rectal probe and was maintained at 37°C. HR and oxygen saturation were monitored using a pulse oximeter (Nonin Medical, Plymouth, MN). The rat was placed on a stereotaxic apparatus (David Kopf Instruments). A 2-cm, 1-im. incision was made to expose the skull. A burr hole (4-mm diameter) was made in the occipital bone, according to the following coordinates: 12.0–12.5 mm caudal from the bregma; 2.0–2.5 mm from the midline, 8.5 mm deep from the dural surface. One hundred nanoliters of a retrogradely transported tracer that is retrogradely transported, rhodamine-labeled fluorescent microspheres in suspension (0.04 μm, Molecular Probes, Eugene, OR) were unilaterally injected into the rVLM through a glass micropipette. The wound was sutured shut. The microspheres were transported during the 10- to 12-day recovery and maintenance period.

Terminal procedures occurred 10–12 days after administration of the retrograde tracer. Rats were re-anesthetized with the ketamine-xylazine, as described above. After tracheostomy and intubation, cannulation and monitoring for vital signs were similar to the procedures described earlier above. Animals were stabilized for 4 h. Then EA or sham-operated controls for EA were conducted over a 30-min period (as described, see below). As described in our previous studies (20), 90 min following termination of EA or the control procedure, rats were deeply anesthetized with a large dose of the ketamine-xylazine (0.5–0.7 ml im). Transcardial perfusion was performed using 500 ml of 0.9% saline solution followed by 500 ml of 4% paraformaldehyde. The medulla oblongata was harvested and sliced into coronal sections (30 μm) with a cryostat microtome (Leica CM1850 Heidelberger Strasse, Nussloch, Germany). The sections were scanned to identify the sites of microinjection of the microsphere tracer. If the tracer injections of microsphere tracers were located in the right region of the rVLM, identified according to their best convergence of splanchnic and median nerves, NRP, and baroreceptor afferents. Then we examined for cardiac rhythmicity and either direct projection to IML using antidromic stimulation (n = 5) or the relationship of rVLM activity with renal sympathetic discharge (n = 10). Due to the complexity of the preparation, we found that we could not reliably insert an electrode into the IML to identify sympathetic premotoneurons. However, demonstration of a relationship between rVLM and renal sympathetic discharge allowed classification of the remainder of rVLM neurons as presympathetic.

We used a number of techniques to categorize rVLM neurons. First, we identified cells that receive visceral and somatic afferent convergent input. Convergence of splanchnic and median nerve input evoked activity of 30 stimuli at 2 Hz over a 15-s period was recorded to allow construction of peristimulus time histograms. Evoked discharge was established as the difference between peak response and prestimulation activity. Peristimulus histograms were used to evaluate rVLM neuronal responses to stimulation of the NRP substrate and blockade of serotonin rVLM receptors. Second, in some cases, we antidromically evoked activity in rVLM neurons from the IML, which was stimulated at a frequency of 2 Hz and a duration of 0.5 ms, to
locate premotor sympathetic cells. Neurons that responded to antidiromic stimulation were examined further for constant latency, stable threshold of the evoked all-or-none response, and a faithful response to high rates of stimulation (100–200 Hz). Regular responses to high-frequency stimulation helped establish an absence of variable synaptic delay. Then the neurons were evaluated for collision of IML-evoked antidromic action potentials and splanchnic or median nerve-evoked orthodromic activity. The refractory period also was measured to determine the critical time interval (latency plus refractory period) during which the ortho- and antidromic spikes collide. The conduction velocity of premotoneurons was determined from the distance between the recording and stimulating electrodes and the antidromic latency. Third, time and frequency domain analyses on arterial pulse and histograms of sympathetic discharge and rVLM neuronal activity were constructed as in our laboratory’s previous studies (20, 22, 36).

RESULTS

Role of NRP in Acupuncture Effect

The cardiovascular sympathoexcitatory responses to repeated stimulation of the gallbladder with BK every 10 min...
were consistent. HR and MAP before the onset of each reflex response were consistent throughout this protocol (Fig. 1A). Sympathoexcitatory cardiovascular responses were reduced by EA and remained inhibited after microinjection of saline into the NRP. However, depolarization blockade of neurons in the NRP with KA reversed the EA-related inhibition of the cardiovascular sympathetic reflex (Fig. 1B and C). Baseline blood pressure did not change following microinjection of KA.

Role of 5-HT1A Receptors in the rVLM During Acupuncture

Stimulation by 30 min of EA reduced the cardiovascular reflex responses during and for over 40 min after activation of the median nerves. Microinjection of saline into the rVLM did not affect the EA-related inhibition (Fig. 2A). Blockade of 5-HT1A receptors in the rVLM reversed the inhibitory effects of EA from 18 ± 4 to 29 ± 2 mmHg, but did not influence the primary cardiovascular reflex responses (Fig. 2B and C).

Seropectogenic Input From NRP to rVLM

Neurons in the NRP were activated sequentially with DLH four times, to mimic EA, during repeated gallbladder stimulation every 10 min. The sympathoexcitatory cardiovascular responses were reduced after each DLH microinjection. Baseline arterial blood pressure was decreased transiently by 5–10 mmHg with each NRP-DLH microinjection. Serotonergic projections to the rVLM were identified by noting the significant reversal of the DLH inhibition of the cardiovascular reflex response following administration of WAY-100635 in the rVLM (Fig. 2D).

In addition to reflex cardiovascular responses, we evaluated rVLM neuronal activity to confirm the role of the NRP-rVLM serotonergic connection in the EA response. We studied only neurons that received convergent somatic and visceral input and were responsive to baroreceptor afferent stimulation and thus could be classified as cardiovascular excitatory cells. In this group of neurons, the change in MAP of 50 ± 3 mmHg with nitroglycerin increased rVLM activity from 2.6 ± 0.93 to 3.5 ± 1.0 spikes/s. Conversely, phenylephrine decreased the firing rate from 2.3 ± 0.63 to 1.8 ± 0.58 spikes/s in response to an increase in blood pressure of 108 ± 34 mmHg. We recorded activity of four out of five cells that were identified as premotoneurons using the collision technique. Another five cardiovascular rVLM neurons in which we did not examine antidromic input or record together with the renal multiunit sympathetic nerve activity received convergent input from the NRP, splanchnic, baroreceptor, and median nerves. The remaining eight rVLM neurons were recorded simultaneously with RSN activity. All eight rVLM neurons studied were found to be correlated with RSN activity, while four others, as noted above, were identified as premotor using collision from the IML. Thirteen of fourteen rVLM neurons examined received input from the NRP. Frequency domain analysis of RSN and rVLM autospectra generated a coherence of 0.64 ± 0.02 at a frequency of 2.6 ± 0.1 Hz (equivalent to a HR of 156
beats/min). Baseline activity of this group of rVLM neurons averaged 2.9 ± 0.75 spikes/s. Coherence values and baseline activity were not different between the two groups of rVLM neurons, i.e., four premotor and 14 presympathetic rVLM neurons. An example of an rVLM neuron whose activity was correlated with the RSN and arterial blood pressure and that demonstrated significant cardiac rhythmicity using coherence analysis is shown in Fig. 3. Another rVLM cell shown in Fig. 4 was identified as premotoneuron that projected to the IML, as shown by collision of an antidromically evoked spike with a splanchnic nerve-induced orthodromic action potential.

Sympathoexcitatory cardiovascular rVLM neurons that received median nerve and NRP input demonstrated consistent splanchnic nerve-evoked responses when stimulated every 10 min (Fig. 5A). The discharge rate of rVLM neurons was decreased after each of four DLH NRP microinjections (Fig. 5B). Blockade of rVLM 5HT1A receptors reversed the inhibitory action of NRP activation (Fig. 5C).

**Anatomical Location of Recording and Stimulating Sites**

All rVLM recording and microinjection sites were confined to an area 1.8–4.4 mm rostral to the obex. The sites were located 2.87–3.75 mm lateral to the midline and 0.1–0.8 mm from the ventrolateral surface in the region of the rVLM, which is lateral to the inferior olivary nucleus and ventral and medial to the facial and retrofacial nuclei, as described by several authors, including ourselves (6, 15, 37) (Fig. 6). Microinjection sites in the NRP were located in the midline between the inferior olivary nucleus and the pyramidal tracts. The majority of the injection sites in the raphe pallidus were located 3–4 mm rostral to the obex. One rVLM neuron that did not receive input from the NRP was located 2.1 mm rostral to the obex. All sites of stimulation of the spinal cord between T2 and T5 were identified to be in the IML, located in the central lateral gray area of the spinal cord, as described by Morrison and Gebber (29).

Fig. 2. Role of serotonin1A or 5-hydroxytryptamine (5-HT1A) receptors in rostral ventrolateral medulla (rVLM) during EA-cardiovascular modulation. A: 30-min stimulation of P5-P6 led to prolonged attenuation of the increase in BP in the presence of saline vehicle microinjection into the rVLM. B: the serotonin antagonist (WAY-100635), however, reversed the effects of EA. C: in contrast, the antagonist did not influence the cardiovascular responses in the absence of EA. D: microinjection of dl-homocysteic acid (DLH) into the NRP, like EA, caused sympathoinhibition, a response that was reversed by administration of the serotonin antagonist into the rVLM. Bars represent increases in MAP induced by gallbladder stimulation. Means ± SE below histogram bars represent baseline MAP. *Significantly different compared with control MAP, P < 0.05.
Fig. 3. Characterization of a cardiovascular sympathoexcitatory rVLM neuron that received convergent input from splanchnic nerve, median nerve, NRP, and baroreceptors. I (top): the activities of the renal sympathetic nerve (RSN) and the rVLM neuron are shown. II (bottom), A: the rVLM neuron displayed similar rhythmicity with renal sympathetic activity documented as a coherence of 0.6 at a frequency at 1.9 Hz and autospectra (AS). B: the neuron also demonstrated a close correlation in time, as measured with spike-triggered averaging. C and D: another rVLM cell (control neuron) and its correlation with renal sympathetic activity. Note lack of coherence and correlation. E: the same rVLM neuron discharged at an identical frequency of 1.9 Hz and demonstrated a coherence of 0.52 when its activity was gated with BP. F: the pulse-triggered averaging of BP and rVLM discharge frequency of this neuron. AS, ?.
NRP Neurons Colabeled With Retrograde Tracer and c-Fos in the NRP

In both EA-treated (n/H11005/5) and control rats (n/H11005/4), we observed that perikarya labeled with the retrograde microsphere tracer were distributed rostrocaudally throughout the NRP, following microinjection into the rVLM. Like our findings in cats (14), we noted more neurons with Fos immunoreactivity in EA-treated rats than in controls (19/H11006/3 vs. 7/H11006/2; P/H11021/0.05) in the NRP. Importantly, we also found Fos nuclei colocalized with neurons that were labeled with the retrograde tracer from the rVLM. These double-labeled neurons also were observed significantly more frequently in EA-treated rats than in controls (9/H11006/1 vs. 3/H11006/1; P/H11021/0.05), while there were similar numbers of neurons labeled with the retrograde tracer in NRP of both groups (24/H11006/3 vs. 21/H11006/4; EA treated vs. controls; P/H11022/0.05). Photomicrographs in Fig. 7 show examples of confocal images displaying a neuron double-labeled with c-Fos (following median nerve stimulation) and microspheres in the NRP of an EA-treated rat.

DISCUSSION

Neurons in NRP activated by stimulation of acupoints P5-P6 overlying the median nerves contain serotonin, among other neurotransmitters (14). The medullary raphe nuclei are known to modulate autonomic reflexes (4). In this respect, activation of neurons in the raphe pallidus that project to sympathetic premotoneurons in the rVLM decreases baseline blood pressure through sympathoinhibition (3, 9, 25, 40). Similarly, EA modulates rVLM neurons to inhibit cardiovascular autonomic responses (35, 38). The present study provides several novel observations: 1) the NRP is involved in cardiovascular reflex modulation by EA; 2) EA modulates cardiovascular responses through 5-HT1A receptors in the rVLM; 3) a direct projection from EA-activated NRP neurons to rVLM exist; and 4) serotonergic projections from the NRP to the rVLM contribute to the EA-cardiovascular responses.

Serotonin is an important neurotransmitter in the medullary raphe. The caudal raphe, where the majority of EA-activated neurons exist (14), contains ~15% of all serotonergic neurons in the brain (17). Serotonin plays a role in many conditions, including mood disorders, nociception, movement, sleep cycles, and autonomic cardiovascular regulation (17, 31). The raphe obscurus, for example, inhibits cardiovascular reflexes through a serotonergic mechanism (41). We recently have...
shown significant activation of neurons in the medullary raphe pallidus following stimulation at P5-P6. EA-induces activation of c-Fos containing neurons that often contain serotonin in a region 3.5 mm rostral to the obex (14), which coincides with the site of microinjections in the present study. Chemical and EA-related electrical activation of NRP neurons in this region demonstrate serotonergic input to the rVLM, which, in turn, decreases cardiovascular reflex sympathoactivation, thus underscoring the importance of serotonin in the cardiovascular modulation by EA.

Caudal medullary raphe neurons related to the cardiac cycle and sympathetic nerve discharge are frequently sympathoinhibitory (26). In this respect, microinjection of glutamate into the raphe pallidus decreases MAP and RSN activity and the discharge rate of sympathoexcitatory rVLM neurons (9, 40). In the present study, splanchnic nerve-evoked activation of sympathoexcitatory presympathetic cardiovascular rVLM neurons, as well as visceral sympathoexcitatory reflexes, was inhibited by DLH-induced activation of the NRP, as a surrogate for EA. The NRP-rVLM projections that participate in the EA modulatory response depend, at least in part, on activation of 5-HT1A receptors.

There are two potential limitations in the present study. First, we used rats rather than cats to demonstrate the presence of cells with direct projections from the NRP to the rVLM that were activated by EA. However, our laboratory has previously shown that the anatomic circuitry participating in the EA-cardiovascular inhibitory response in rats and cats is virtually identical (1, 20). We, therefore, believe that our data obtained in rats with respect to this projection likely also apply to cats.

Second, we found that only about one-fourth of the rVLM neurons examined could be identified as premotor rVLM neurons. On the other hand, we were able to demonstrate that the remainder of the rVLM neurons were presympathetic in nature, in that they showed a strong relationship to sympathetic outflow. As such, the rVLM neurons evaluated in the present study all appeared to play a role in regulating sympathetic nerve activity.
We have identified a long-loop pathway involved in EA modulation of excitatory cardiovascular reflexes. More specifically, neurons in the hypothalamic arcuate nucleus, vPAG, and rVLM process information during somatic afferent stimulation that ultimately leads to prolonged (often >90 min) inhibition of sympathetic outflow following a single 30-min application of acupuncture (20, 22, 36–38). Reciprocal projections between the arcuate nucleus and the vPAG likely contribute, in part, to the long-lasting EA inhibition of sympathoexcitatory and cardiovascualr responses (21, 35). Serotonergic projections from the NRP to the rVLM may form an important part of this long-loop pathway.

The medullary raphe nuclei receive input from midbrain regions, including the vPAG (11). Activation of neurons in the vPAG inhibits activity of rVLM premotor sympathetic neurons (38) and is essential for the EA-cardiovascular sympathoinhibition in the rVLM (20). Direct projections from the vPAG to the rVLM exist (13). However, it is unclear if EA relies on a direct or indirect pathway from the vPAG to the rVLM, with the latter likely processed through the NRP. Additional studies will need to be conducted to determine the importance of direct vs. indirect connections between the vPAG and the rVLM in the EA-cardiovascular response. However, our observation that 5-HT1A receptor activation is required for the full expression of the EA-related sympathoinhibition suggests that the NRP is a required component, since this region is so rich in serotonin (17).

Helke et al. (16) have demonstrated direct projections from the NRP to the IML of the spinal cord. These projections are serotonergic and are thus inhibitory in nature. Although we have shown an important connection from the NRP that is processed through the rVLM, future studies will need to evaluate possible direct connections from the raphe to sympathetic motoneurons in the spinal cord IML. We do believe, however, that the rVLM connections are of paramount importance, since blockade of neurons in this region largely eliminates the EA-cardiovascular response (10, 19, 35–37).

Conclusion

The present study shows that, during EA, serotonergic neurons in the medullary raphe, in particular, the raphe pallidus, project to sympathoexcitatory cardiovascular neurons in the rVLM and through a 5-HT1A receptor mechanism participate in EA-related sympathoinhibition.

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DISCLOSURES

No conflicts of interest are declared by the author(s).

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