Microinjections of α-melanocyte stimulating hormone into the nucleus ambiguus of the rat elicit vagally mediated bradycardia

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Chitravanshi VC, Bhatt S, Sapru HN. Microinjections of α-melanocyte stimulating hormone into the nucleus ambiguus of the rat elicit vagally mediated bradycardia. Am J Physiol Regul Integr Comp Physiol 296: R1402–R1411, 2009. First published March 18, 2009; doi:10.1152/ajpregu.90978.2008.—Neurons that immunostain for alpha-melanocyte stimulating hormone (α-MSH) have been identified in the nucleus ambiguus (nAmb). The presence of mRNA for melanocortin type 4 receptors (MC4Rs) has also been reported in this nucleus. On the basis of this information, it was hypothesized that activation of MC4Rs in the nAmb may play a role in the regulation of cardiac function. This hypothesis was tested in urethane-anesthetized, artificially ventilated, adult male Wistar rats. Microinjections (30 nl) of α-MSH (0.1, 0.2, 0.4, 0.8, and 1.2 mM) into the nAmb of anesthetized rats elicited decreases in heart rate (HR; 1.3 ± 0.6, 3 ± 1.1, 11 ± 2, 46.3 ± 3, and 43.3 ± 7 bmpm, respectively) and no changes in mean arterial pressure (MAP). Maximum decreases in HR were elicited by 0.8 mM concentration of α-MSH. Bradycardic responses to α-MSH were similar in unanesthetized midcollidicular decerebrate rats. Microinjections of artificial cerebrospinal fluid (30 nl) into the nAmb did not elicit a HR response. Bilateral vagotomy completely abolished α-MSH-induced bradycardia. The decreases in HR elicited by α-MSH (0.8 mM) were completely blocked by a selective MC4R antagonist. Direct application of α-MSH on the nAmb neurons increased their firing, which was blocked by prior applications of the MC4R antagonist. Microinjections of the MC4R antagonist into the nAmb did not alter reflex bradycardic responses elicited by intravenous infusions of phenylephrine, suggesting that MC4Rs did not play a role in mediating the parasympathetic component of baroreflex-decrebrate bradycardia. These results indicated that α-MSH microinjections into the nAmb exert excitatory effects on parasympathetic preganglionic nAmb neurons via MC4Rs, leading to bradycardic responses.

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ALPHA-MELANOCYTE STIMULATING hormone (α-MSH) is one of the major melanotropins (1, 5, 37). The melanocortin family includes other peptides such as ACTH, β-MSH, γ-MSH, and β-endorphin (5). These peptides are derived from the common precursor proopiomelanocortin (POMC) (1, 5, 37, 46). Neurons containing α-MSH have been identified in the arcuate, dorsomedial, posterior, paraventricular, and lateral hypothalamic nuclei, as well as the nucleus tractus solitarius (NTS) (11, 15, 29). The axons of some α-MSH-containing neurons in the lateral hypothalamic area have been reported to project to the intermediolateral cell column in the thoracic spinal cord (19, 38).

The effects of melanocortins are mediated through the melanocortin receptors (MCRs). Five MCRs (MC1R–MC5R) have been identified (1, 12, 18, 46). They are G protein-coupled receptors that stimulate adenylate cyclase. MC1R is primarily present in melanocytes, where it regulates pigmentation of the skin. MC2R is an ACTH receptor and is present primarily in the adrenal cortex. MC5R is primarily present in the exocrine glands. Of the five MCRs, mainly MC3Rs and MC4Rs are present in the central nervous system (CNS). The CNS regions where MC3Rs and MC4Rs are present include the cortex, limbic system, thalamus, hypothalamus, midbrain, brain stem, and spinal cord (1, 12, 46).

Melanocortins have been implicated in several physiological functions, including regulation of body weight, sexual behavior, and cardiovascular function (3, 13, 14, 16, 22, 28, 31, 33, 35, 43, 47). Melanocortins may also play a role in stress since their levels have been reported to be elevated in stressful situations (21). These peptides have also been reported to provide neuroprotection in experimental ischemic stroke (7, 8). Recently, melanocortins have been reported to reverse hemorrhagic shock conditions and provide strong protection against myocardial ischemia/reperfusion injury in experimental animals and humans (9, 10); these effects are mediated via MC4Rs in the brain and involve activation of an effenter vagal cholinergic pathway (26). Central mechanisms by which melanocortins activate this effenter vagal cholinergic pathway have not been elucidated. In the rat, the nucleus ambiguus (nAmb) is the predominant source of parasympathetic innervation to the heart (24, 41). Neuronal networks, which immunostain for α-MSH, have been identified in the nAmb (30). The presence of MC4R mRNA has also been identified in this nucleus (27, 40). On the basis of this information, it was hypothesized that α-MSH may activate the parasympathetic preganglionic neurons in the nAmb and increase the activity of vagal innervation to the heart. There are no reports in the literature regarding cardiac responses to α-MSH in this nucleus. The present investigation was, therefore, undertaken to investigate the nature and mechanism of cardiac responses to α-MSH in the nAmb. The information generated will be useful in unraveling the role of melanocortins in the regulation of cardiovascular function in different physiological and pathophysiological situations.

MATERIALS AND METHODS

General procedures. Experiments were done in adult male Wistar rats (n = 73) (Charles River Laboratories, Wilmington, MA), weighing 300–350 g. All animals were housed under controlled conditions with a 12:12-h light-dark cycle. Food and water were available to the animals ad libitum. The experiments were performed according to the National Institutes of Health’s “Guide for the Care and Use of Laboratory Animals” (7th ed., 1996) and with the approval of the Institutional Animal Care and Use Committee of the University of Medicine and Dentistry-New Jersey Medical School.

The general procedures have been described in detail elsewhere (4, 17). Briefly, the rats were anesthetized with inhalation of isoflurane...
Injection was 5–10 s. Microinjections (30 nl) of artificial cerebrospinal fluid were made using a dorsal approach. Four-barreled glass micropipettes (tip size 20–40 μm) were mounted on a micromanipulator (model 1460, David Kopf Instruments). The parietal bones were removed, and bradyphrenia in the nAmb were identified by microinjections of L-Glu (5 mM). The volume of all microinjections into the nAmb was 30 nl; the selection of this volume was based on our preliminary studies, in which the volume of injected solution (2 nl) was visually confirmed under a modified binocular horizontal microscope. Controls consisted of 2 nl of aCSF (pH 7.4). The involvement of recorded nAmb neurons in cardiovascular regulation was ascertained by their excitation in response to bolus injections of PE (2–4 μg/kg iv).

Immunohistochemical staining for MC4Rs. For immunohistochemical identification of MC4Rs, the rats were deeply anesthetized with urethane and perfused transcardially with 10% sucrose solution followed by 4% paraformaldehyde in PBS. The brain was removed and stored in 4% paraformaldehyde at 4°C overnight, and then placed in a 30% sucrose solution until it sank to the bottom of the container (usually 2–4 days). The sections of the brain were cut (30–40 μm) at 15°C, using a cryostat (model CM1900, Leica Microsystems, Bannockburn, IL), placed on subbed slides and stored at –20°C. Subsequently, the sections were brought to room temperature and washed with PBS containing 0.3% Triton (TPBS). The sections were then treated with 0.02% hydrogen peroxide for 2 min and washed, followed by 1 h incubation in blocking buffer consisting of TPBS and goat serum (5%, Vector Laboratories, Burlingame, CA). The sections were then incubated overnight at 4°C with primary antibody (rabbit polyclonal anti-MC4R; Abcam, Boston, MA) diluted in blocking buffer (1:1,000), followed by 3 washes in TPBS for 5 min each. The sections were then incubated with a biotinylated secondary antibody (goat anti-rabbit IgG; Santa Cruz Biotechnology, Santa Cruz, CA) at room temperature for 2 h, washed and incubated with avidin–biotin complex conjugated to peroxidase (prepared 30 min prior to use; ABC Elite Kit; Vector Laboratories). The sections were then washed and treated with a stabilized solution of active dianinobenzidine (“Stable DAB”, Vector Laboratories) until completion of the reaction (at least 20 min).

Decerebration. To exclude the effects of urethane on α-MSH-induced responses, experiments were performed on decerebrate rats. The procedure for decerebration was similar to that reported earlier (3, 16). Briefly, anesthesia was induced and maintained by isoflurane. To minimize bleeding, the external and internal carotid, as well as the pterygopalatine arteries were ligated bilaterally under an operating microscope (OPMI-1; Carl Zeiss, Thornwood, NY), while all other branches in the carotid sinus region remained patent for continued blood flow in this region. The rats were placed in a prone position in a stereotaxic instrument (David Kopf Instruments). The parietal bones were removed, and the sagittal sinus was ligated rostrally and caudally and sectioned between the ligatures. A transection was made at microludicial level, and the rostral portion of the brain was removed by suction. The cranial cavity was then packed with cotton balls. Tracheal intubation of isoflurane was discontinued, and a stabilization period of 60 min was allowed.

Baroreflex function test. To measure the parasympathetic component of the baroreflex, phenylephrine (PE) was infused intravenously, and baroreflex function curves were obtained by plotting reflex decreases in HR in response to increases in MAP. Approximately linear increase in MAP was induced by infusing PE (125 μg/ml) with a 5-ml syringe connected to the femoral venous cannula and mounted on an infusion pump (model 341, Sage Instruments, Cambridge, MA). PE was administered continuously every 30 s by ramped infusion at a rate of 0.12, 0.17, and 0.25 ml/min until the MAP increased by 60 mmHg. The protocol was repeated after bilateral microinjections of aCSF and MC4R antagonist (0.2 mM) into the nAmb (for selection of the MC4R antagonist concentration, see Blockade of α-MSH responses by MC4R antagonist in the RESULTS). In each experiment, PE infusions were made before any microinjections into the nAmb (control), after microinjection of aCSF, and after microinjection of MC4R antagonist; the interval between PE infusions was at least 20 min of equilibration.

Extracellular neuronal recording. The procedure for extracellular neuronal recording has been described elsewhere (17). Briefly, five-barreled glass micropipettes (Medical Systems, Greenvale, NY) were used. The tip size was adjusted, so that the resistance of the barrels was 4–8 MΩhms. In this configuration, the recording barrel was in the center of the micropipette tip (~5–10 μm), with ejection barrels surrounding it. The central barrel used for recording was filled with 4 M NaCl, and the other barrels contained aCSF, L-Glu, α-MSH, and MC4R antagonist. The micropipette was inserted into the nAmb using the coordinates mentioned earlier. The extracellularly recorded neuronal activity was filtered (100–10,000 Hz) and amplified (×10,000–20,000) (using model DAM-80 amplifier with low-noise headstage probe; World Precision Instruments) and window discriminator (Fredrick Haer, Brunswick, ME). The amplified signals were digitized and analyzed using 1401 A/D converter and Spike 2 software (Cambridge Electronic Design) and stored on a computer hard drive. Ejection of the contents in different barrels on neurons was accomplished by application of pressure pulses (15-ms duration, 20 psi), and the volume of ejected solution (2 nl) was visually confirmed under a modified binocular horizontal microscope. Controls consisted of 2 nl of aCSF (pH 7.4). The involvement of recorded nAmb neurons in cardiovascular regulation was ascertained by their excitation in response to bolus injections of PE (2–4 μg/kg iv).
10 min), and again washed. The sections were then either coverslipped with glycerol or dehydrated with ethyl alcohol, treated with xylene, and coverslipped with Permount (Sigma-Aldrich, St. Louis, MO). Photomicrographs were then taken with a digital color camera with megapixel resolution coupled to an IEEE 1394 port on a personal computer. Neurulucida software (Micro Bright Field, Williston, VT) was used for obtaining the pictures.

The control procedures used to determine the specificity of immunohistochemical reactions were as follows: the primary antibody was replaced with serum or 0.01 M PBS, pH = 7.4, containing 0.3% Triton and 1% serum, and the secondary antibody was replaced with 1% bovine calf serum or 0.01 M PBS.

Histology. Typical sites of microinjections in the nAmb were marked by microinjections of diluted India ink. The animals were perfused and fixed with 4% paraformaldehyde, and serial sections of the medulla were cut (40 μm) in a vibratome, mounted on slides, dehydrated, cleared, and stained with cresyl violet. The microinjection sites were identified using a microscope. The sections were photographed and compared with a standard atlas (32).

Drugs and chemicals. The following drugs and chemicals were used: α-MSH (American Peptides, Vista, CA), cyclo [(CO-(CH2)2- CO-D-Nal(2’)-Arg-Trp-Lys)-NH2] (MC4R antagonist; ref. 2) (Peptide International, Louisville, KY), isoflurane (Baxter Pharmaceutical Products, Deerfield, IL), L-glutamate monosodium, L-phenylephrine hydrochloride, and urethane. All of the solutions for the microinjections were freshly prepared in aCSF. The osmolality of aCSF (pH 7.4) was 298 mOsmol/kg, and the concentrations (mM) of different constituents [mentioned in brackets] were as follows: NaCl [152], KCl [3], CaCl2 [1.2], MgCl2 [0.8], dextrose [3.4], and HEPES [5]. The concentration of drugs refers to their salts where applicable. The sources of other drugs and chemicals were either Sigma-Aldrich or Fisher Scientific (Suwanee, GA), unless indicated otherwise.

Statistical analyses. For comparison of HR responses, the means ± SE were calculated for maximum changes in this value in response to microinjections of α-MSH or L-Glu into the nAmb. In the concentration-response studies, comparisons of the maximum decreases in HR in different groups of rats were made by using an ANOVA followed by Tukey-Kramer’s multiple-comparison test. One-way ANOVA followed by Tukey-Kramer’s multiple-comparison test was also used to compare the control reflex bradycardic responses to increases in MAP induced by intravenous infusions of PE before any microinjections into the nAmb, after bilateral microinjections of aCSF and after MC4R antagonist into the nAmb. In baroreflex function studies, maximum bradycardic responses at each increment of MAP (10, 20, 30, 40, 50, and 60 mmHg) were used for statistical calculations. In experiments testing for tachyphylaxis and effect of MC4R antagonist, comparisons of the maximum decreases in HR elicited by microinjection of α-MSH into the nAmb were made by using repeated-measures ANOVA followed by Tukey-Kramer’s multiple comparison. Student’s paired t-test was used for comparisons of maximum decreases in HR elicited by the following: 1) microinjection of α-MSH into the nAmb before and after the bilateral vagotomy, and 2) microinjection of L-Glu into the nAmb before and after the microinjections of MC4R antagonist. Unpaired t-test was used for comparisons of the maximum decreases in HR elicited by microinjection of α-MSH into the nAmb in anesthetized and decerebrate rats.

For the analysis of neuronal activity, the control firing rate represented the average of firing during the 1- to 2-s period before neuronal activation. Maximum increase in firing rate (averaged for the 1- to 2-s period) in response to direct application of α-MSH or L-Glu. In experiments involving intravenous bolus injections of PE, maximal spike activity of the neuron was compared with the basal neuronal activity, at the peak increase in MAP to generate statistical analysis. The mean values of the increase in neuronal activity were compared using Student’s paired t-test. In all cases, the differences were considered significant at P < 0.05.

RESULTS

Baseline values for MAP and HR in urethane-anesthetized rats were 99.7 ± 2 mmHg and 405 ± 9 bpm, respectively (n = 64). The values for baseline MAP and HR in the decerebrate rats (n = 9) were 83 ± 3 mmHg and 428 ± 10 bpm, respectively. There were no significant differences (P > 0.05) between the baseline values of MAP and HR in urethane-anesthetized and decerebrate rats.

Concentration-response of α-MSH. Five different concentrations (0.1, 0.2, 0.4, 0.8, and 1.2 mM) of α-MSH, 30 nl each, were used for concentration-response experiments. Fifteen rats were used for concentration-response studies. In one group (n = 5), 2 concentrations (0.1 and 0.2 mM) were filled in two separate barrels of the 4-barreled micropipette, while the other two barrels contained L-Glu (5 mM) and aCSF. First, the nAmb was identified by microinjections of L-Glu, which was followed by testing lack of any responses to microinjections of aCSF. Then, the responses to the two concentrations of α-MSH were studied. The interval between the microinjections of α-MSH was at least 40 min to avoid tachyphylaxis. The sequence of microinjections of the two concentrations of α-MSH was changed in different rats. In the second group of rats (n = 5), the same protocol was used with two different concentrations (0.4 and 0.8 mM) of α-MSH. In the third group of rats (n = 5), the procedure was similar except that only one concentration (1.2 mM) was used. Unilateral microinjections of L-Glu (5 mM) were used to identify the nAmb; bradycardia (56 ± 6 bpm), unaccompanied by any change in MAP, was observed. The interval between the microinjections of L-Glu and other agents was at least 5 min. Microinjections of different concentrations (0.1, 0.2, 0.4, 0.8, and 1.2 mM) of α-MSH into the nAmb elicited decreases in HR (1.3 ± 0.6, 3 ± 1, 11 ± 2, 46.3 ± 3, and 43.3 ± 7, bpm; Fig. 1A) (n = 15). In this and other series of experiments,
microinjections (30 nl) of aCSF into the nAmb elicited no responses. The maximal decrease in HR was elicited by 0.8 mM concentration; the bradycardic response to a higher concentration of α-MSH (1.2 mM) was not significantly different from that of 0.8 mM concentration. Therefore, 0.8 mM concentration of α-MSH was selected for further studies in other groups of rats. The onset, peak, and duration of the responses elicited by 0.8 mM concentration of α-MSH were 5–15 s, 40–90 s, and 10–15 min, respectively.

Effect of bilateral vagotomy. In these experiments (n = 7), nAmb was identified by microinjection of L-Glu (5 mM); a decrease in HR (81.4 ± 11 bpm) was observed. Five minutes later, microinjections of α-MSH (0.8 mM) at the same site elicited a bradycardia (38.6 ± 4 bpm). Forty minutes later, bilateral vagotomy was performed, and a 10-min period of stabilization was allowed. Bilateral vagotomy did not change the basal MAP; the MAP values before and after bilateral vagotomy were 103.3 ± 6 and 102.5 ± 6 mmHg, respectively (P > 0.05). However, bilateral vagotomy increased the basal HR significantly; the basal HR values before and after the vagotomy were 415 ± 8 and 438.3 ± 8 bpm, respectively (P < 0.01). Microinjections of L-Glu, as well as α-MSH into the same site in the nAmb failed to elicited bradycardic responses after bilateral vagotomy (Fig. 1B).

Reproducibility of α-MSH-induced responses. Absence of tachyphylaxis to repeated microinjections of α-MSH was tested as follows (n = 5). The concentration of α-MSH that elicited maximal bradycardic responses (0.8 mM) was microinjected into the nAmb at least 3 times, at 40-min intervals. The decreases in HR induced by three consecutive microinjections of α-MSH were 46.3 ± 3, 43.3 ± 7, and 47.6 ± 3 bpm, respectively (P > 0.05). Thus, no tachyphylaxis of responses was observed with repeated microinjections of α-MSH when the interval between injections was 40 min.

Site specificity of α-MSH responses. The concentrations of α-MSH that elicited maximal bradycardic responses when microinjected into the nAmb (n = 5) did not elicit a response when injected intravenously, indicating that leakage of the drug, if any, from the injection site to the peripheral circulation was not responsible for the observed responses. The bradycardic responses elicited from the nAmb were site specific because microinjections of α-MSH (0.8 mM) or L-Glu (5 mM) into the adjacent areas (e.g., ventral region of the dorsal medullary reticular nucleus; 0.6 mm rostral and 2.3 mm lateral to the CS, and 2.6 mm deep from the dorsal medullary surface) elicited no HR responses.

Blockade of α-MSH responses by MC4R antagonist. Prior to microinjections of α-MSH or MC4R antagonist, the nAmb was always identified by microinjections of L-Glu (5 mM), which elicited decreases in HR (76 ± 10 bpm) without concomitant changes in MAP. In one group of rats (n = 5), 5 min after the microinjection of L-Glu, microinjection of the maximally effective concentration of α-MSH (0.8 mM) into the nAmb elicited a decrease in HR (34 ± 4, bpm). Forty minutes later, the MC4R antagonist (0.1 mM) was microinjected at the same site, which was followed by another microinjection of α-MSH. The bradycardic responses to microinjections of α-MSH (0.8 mM) were attenuated (15 ± 4 bpm) by prior microinjections of MC4R antagonist into the nAmb, but the reduction in response was not statistically significant (P > 0.05). Forty minutes later, α-MSH was microinjected again at the same site, and a bradycardia (20 ± 2 bpm) was observed, indicating that there was a recovery of responses (Fig. 2A). In another group of rats (n = 10), microinjection of α-MSH (0.8 mM) into the nAmb elicited a decrease in HR (43 ± 3 bpm), which was completely blocked (1.5 ± 1 bpm) by prior microinjections of a higher concentration (0.2 mM) of the MC4R antagonist (P < 0.05). Recovery of α-MSH-induced bradycardic responses (38 ± 3 bpm) was observed within 40 min (Fig. 2B). Microinjections of the MC4R antagonist (0.1 mM) did not alter the responses to L-Glu; the decreases in HR before and after the microinjection of the antagonist were 76 ± 10 and 81 ± 11 bpm, respectively (Fig. 2C). Even higher concentration of the antagonist (0.2 mM) did not alter the responses to L-Glu; the decreases in HR before and after the microinjection of the antagonist were 69 ± 8 and 90 ± 20 bpm, respectively (Fig. 2D). Microinjections of aCSF did not alter the responses to α-MSH. Microinjections of the MC4R antagonist alone into the nAmb did not elicit significant cardiovascular responses. A typical tracing of the blockade of α-MSH responses in the nAmb is shown in Fig. 3.

Effect of α-MSH in decerebrate rats. The nAmb was identified by microinjection of L-Glu (5 mM) in a group of decerebrate rats (n = 9); a decrease in HR (168.9 ± 18 bpm) was observed. Five minutes later, microinjections of α-MSH (0.8 mM) at the same site elicited bradycardia (43.9 ± 6 bpm) with no changes in MAP.

Effect of MC4R antagonist on baroreflex. In a group of rats (n = 5), the nAmb was identified bilaterally by microinjections of L-Glu (5 mM); the decrease in HR was 95.8 ± 17.2 bpm. The following three protocols were used to test the baroreceptor function (Fig. 4). First, control baroreflex responses were obtained before any microinjections into the nAmb; reflex decreases in HR (% change from basal value) were 1.06 ± 0.33, 3.5 ± 1.7, and 3.2 ± 1.8, respectively (n = 5). Microinjections of MC4R antagonist (0.1 mM) did not alter the responses to α-MSH at the same site in the nAmb (n = 5) did not elicit a response when injected intravenously, indicating that leakage of the drug, if any, from the injection site to the peripheral circulation was not responsible for the observed responses. 

AJP-Regul Integr Comp Physiol • VOL 296 • MAY 2009 • www.ajpregu.org

Fig. 2. Effect of microinjections of MC4R antagonist on alpha-MSH-induced bradycardia. A: microinjections of the smaller concentration (0.1 mM) of the antagonist attenuated bradycardic responses elicited by alpha-MSH into the nAmb, but the attenuation was not statistically significant (P > 0.05) (n = 5). The responses to alpha-MSH recovered in about 40 min. B: microinjections of a higher concentration of MC4R antagonist (0.2 mM) significantly (P < 0.05) attenuated bradycardic responses elicited by microinjections of alpha-MSH into the nAmb (n = 10). The responses to alpha-MSH recovered in about 40 min. C and D: HR responses to L-Glu (5 mM) were not altered by the microinjection of the MC4R antagonist (0.1 and 0.2 mM). In this and other figures, the concentration of alpha-MSH microinjected into the nAmb was 0.8 mM.
in MAP. Twenty minutes later, the same protocol was repeated after bilateral microinjections of aCSF into the nAmb; reflex decreases in HR were \(0.84 \pm 0.5, 4.28 \pm 1.7, 7 \pm 2.4, 11.6 \pm 2.2, 14.4 \pm 2.1, \) and \(17.75 \pm 3\%\). After an interval of 20 min, the same protocol was repeated after bilateral microinjections of MC4R antagonist (0.2 mM) into the nAmb; reflex decreases in HR were \(0.8 \pm 0.4, 4.82 \pm 1.4, 8.11 \pm 1.9, 9.88 \pm 2, 11.66 \pm 2.1, \) and \(17.55 \pm 2.5\%\). No significant differences \((P > 0.05)\) in the reflex HR decreases in response to different increases in MAP were observed after the microinjections of either aCSF or MC4R antagonist into the nAmb. The concentration of MC4R antagonist (0.2 mM) used in these experiments was previously shown to completely block the effects of the maximally effective concentration of \(\alpha\)-MSH (0.8 mM) in the nAmb (see Blockade of \(\alpha\)-MSH responses by MC4R antagonist).

Effect of \(\alpha\)-MSH on nAmb neurons. Activity was extracelularly recorded from a total of 36 neurons in 7 rats. Twenty-two neurons were spontaneously active, and the remaining 14 were initially silent but were activated by application of L-Glu (5 mM, 2 nl). The increases in neuronal firing mentioned below refer to maximum changes in firing compared with control firing just before the intravenous injection of PE or direct application of drugs. The volume of aCSF or drugs directly ejected onto the neurons was always 2 nl. Involvement of the recorded neurons in HR control was tested by their excitation in response to intravenous bolus injections of PE. Eight of these neurons did not respond to bolus injection of PE; the firing rate before and after PE was \(2.5 \pm 1\) and \(2.2 \pm 1\) spikes/s, respectively. These neurons were not studied any further. Direct application of aCSF to remaining neurons (28 neurons) elicited minimal changes in their firing \((0.35 \pm 0.2\) spikes/s; \(P > 0.05)\) (Fig. 5A). After 3–4 s, an intravenous bolus injection of PE elicited a reflex increase in firing rate \((13.6 \pm 2\) spikes/s; \(P < 0.001)\) (Fig. 5B). The increases in MAP were \(15 \pm 3\) and \(26 \pm 5\) mmHg in response to intravenous bolus injections of 2 and 4 \(\mu\)g/kg of PE, respectively. After an interval of 3–4 s, direct application of L-Glu (5 mM) elicited an increase in firing rate \((19.6 \pm 2\) spikes/s; \(P < 0.001)\) (Fig. 5C). After the neuronal firing returned to basal rates, 3–4 s later, \(\alpha\)-MSH (0.8 mM) was directly applied to these neurons; the neuronal firing rate was significantly increased \((10.6 \pm 1\) spikes/s; \(P < 0.01)\).

Fig. 3. Blockade of \(\alpha\)-MSH responses in the nAmb. Top: tracing shows pulsatile arterial pressure (PAP, mmHg); middle: tracing shows mean arterial pressure (MAP, mmHg); bottom: tracing shows heart rate (HR, beats/min). A: microinjection of L-Glu (5 mM) into the nAmb elicited a decrease in HR but no change in MAP. B: microinjection of artificial cerebrospinal fluid (aCSF) at the same site elicited no responses. C: after 5 min, microinjection of alpha-MSH (0.8 mM) at the same site elicited bradycardic response. After an interval of 40 min, aCSF was microinjected again at the same site. Within 5 min, MC4R antagonist (0.2 mM) was microinjected at the same site (not shown). D: two minutes later, alpha-MSH was again microinjected at the same site; the responses to alpha-MSH were blocked. E: two minutes later, the responses to microinjections of L-Glu (5 mM) were tested; the MC4R antagonist did not alter L-Glu-induced responses. F: bradycardic responses to alpha-MSH recovered within 40 min.

Fig. 4. Baroreflex function curves. Linear regression curves showing the control baroreflex responses before any microinjections into the nAmb (solid circles and straight line), after bilateral microinjections of aCSF (30 nl) into the nAmb (open circles and dotted line), and after bilateral microinjections of MC4R antagonist into the nAmb (open triangles and dashed line). The \(r^2\) values for the regression curves of the bradycardic reflex were 0.993, 0.996, and 0.966 for control, aCSF, and MC4R antagonist groups, respectively.

Fig. 5. Group data of the effect of alpha-MSH on nAmb neurons \((n = 28, 7\) rats). A: direct application of aCSF to the neuron elicited a small change \((P > 0.05)\) in firing rate; the volume of all direct applications onto the neurons was 2 nl. B: intravenous bolus injection of phenylephrine (PE) elicited an increase \((P < 0.001)\) in the neuronal firing. C: application of L-Glu (5 mM) increased \((P < 0.001)\) the neuronal firing. D: application of alpha-MSH (0.8 mM) increased the neuronal firing \((P < 0.01)\). E: prior application of the MC4R antagonist (0.2 mM) to the neuron blocked the excitatory effect of alpha-MSH on these neurons \((P > 0.05)\). F: antagonist did not alter the responses \((P < 0.001)\) to application of L-Glu. G: increase in firing \((P < 0.01)\) in response to alpha-MSH application recovered within 10–15 s.
spikes/s; \( P < 0.01 \) (Fig. 5D). The duration of \( \alpha \)-MSH effect was 6.5 ± 1 s. Subsequently, MC4R antagonist was directly applied to the neuron; no significant change in firing was observed. After an interval of 3–4 s, \( \alpha \)-MSH was again applied onto the neuron; the change in neuronal firing (0.9 ± 0.2 spikes/s) was not statistically significant (\( P > 0.05 \)), indicating that the effect of \( \alpha \)-MSH was blocked by the antagonist (Fig. 5E). The MC4R antagonist did not alter the responses to L-Glu, which elicited an increase in neuronal firing rate (19.6 ± 1.9 spikes/s; \( P < 0.01 \)) (Fig. 5F). The neuronal response to \( \alpha \)-MSH application recovered within 10.5 ± 1 s; application of \( \alpha \)-MSH elicited a significant increase in neuronal firing (9.9 ± 1.1 spikes/s; \( P < 0.01 \)) (Fig. 5G). Typical tracings of a neuronal recording are shown in Fig. 6.

**Immunohistochemical staining of MC4Rs in the nAmb.** Immunostaining for MC4Rs was observed in the nAmb \(( n = 5 \) ). Fig. 7A shows in low magnification the general location of the nAmb in an immunostained section. A cresyl violet-stained adjacent section confirmed the general location of nAmb (Fig. 7B). At a higher magnification of the circled area in Fig. 7A, MC4Rs were seen on the cells and fibers in the nAmb (Fig. 7C). When the primary antibody was omitted as a control procedure, no labeling of MC4Rs in the nAmb was detected (Fig. 7D).

**Histological identification of microinjection sites.** The nAmb sites, where microinjections of L-Glu and \( \alpha \)-MSH elicited bradycardia were marked with India ink in 22 rats. A typical nAmb site marked with India ink (30 nl) is shown in Fig. 8A. Composite diagrams of the microinjection sites in the nAmb are presented in Figs. 8, B–F.

**DISCUSSION**

The main observation in this study was that microinjections of \( \alpha \)-MSH into the nAmb elicited bradycardic responses. This is the first report of central cardiovascular effects of \( \alpha \)-MSH in
the nAmb. Local distortion of brain tissue or any nonspecific effects were not responsible for these observations because microinjections of aCSF into the nAmb did not elicit any response. Concentrations of α-MSH microinjections into the nAmb that elicited decreases in HR did not elicit a response when injected intravenously, indicating that leakage of α-MSH, if any, from the microinjection site into the peripheral circulation was not responsible for the observed responses. The α-MSH-induced bradycardic responses elicited from the nAmb were site specific because similar microinjections into the adjacent areas (e.g., ventral part of the dorsal medullary reticular nucleus; 0.6 mm rostral and 2.3 mm lateral to the CS, and 2.6 mm deep from the dorsal medullary surface) elicited no responses. In view of the proximity of caudal ventrolateral medulla (CVLM) to the nAmb, it is possible that α-MSH-induced bradycardic responses could be partly mediated via the CVLM. However, bilateral vagotomy abolished the α-MSH-induced bradycardic responses could be partly mediated via the CVLM. However, bilateral vagotomy abolished the α-MSH-induced bradycardic responses, excluding this possibility. Moreover, microinjections of L-Glu, used for the identification of nAmb, did not elicit either a pressor or depressor response, suggesting that the RVLM and CVLM did not participate in these responses, respectively. In this context, it may be noted that bradycardia with no concomitant arterial pressure responses to microinjections of L-Glu was consistently used as the criterion for the identification of the nAmb in all experiments.

Microinjections of α-MSH into the nAmb of midcollicular decerebrate rats also elicited bradycardic responses, which were not statistically different from those elicited in urethane-anesthetized rats. These experiments revealed that urethane anesthesia did not alter the responses to α-MSH qualitatively or quantitatively. Moreover, the presence of neural structures located rostral to the brain stem (e.g., hypothalamus) was not necessary for α-MSH-induced effects in the nAmb.

The mechanism of the bradycardic responses elicited by α-MSH microinjections into the nAmb can be explained as follows based on our current knowledge regarding the medullary control of cardiac function (24, 36, 41, 42). α-MSH may have excited parasympathetic preganglionic nAmb neurons, increased the vagal input to the heart, causing bradycardia. This contention was supported by the results of our extracellular neuronal recording in vivo, in which direct application of α-MSH to nAmb neurons resulted in excitation of these neurons. α-MSH-induced excitation of nAmb neurons was mediated via MC4Rs because prior applications of the MC4R antagonist prevented the excitatory effect of α-MSH on these neurons. Moreover, excitation of these neurons by direct applications of L-Glu indicated that activity was being recorded from neurons and not fibers of passage (23). Although the volume ejected by pressure application was very small (2 nl), activation of adjacent interneurons cannot be excluded entirely. Glutamate receptors are likely to be present on the nAmb neurons containing MC4Rs. This possibility is consistent with the ubiquitous distribution of glutamate receptors in the CNS. Reflex activation of nAmb neurons by intravenous bolus injections of PE indicated that the recorded neurons were involved in HR control (34). Lack of responses to aCSF applications indicated that neuronal excitation was not due to an artifact. In agreement with previous reports (23, 24, 25), many (38.8%) neurons in the nAmb were found to be initially silent. There are no reports regarding the effect of α-MSH on extracellular neuronal activity in vivo for comparison of our results. However, patch-clamp studies in vitro have shown that MC4R agonists depolarize some neurons (e.g., POMC neurons in the hypothalamic arcuate nucleus) by decreasing predominantly transient outward potassium (I_A) conductance (39), and this effect is likely to cause an increase in the action potential firing (6).

**Fig. 7.** Immunohistochemical staining of MC4Rs in the nAmb. A: coronal section of the medulla (0.5 mm rostral to the calamus scriptorius) showing immunostained MC4Rs in the nAmb (see circled area). B: cresyl-violet stained coronal section taken at a level adjacent to that shown in A; nAmb is marked by a circle. C: higher magnification (200X) of the circled area in A showing neurons and fibers immunostained for MC4Rs. D: control section showing no immunostaining for MC4Rs when incubation with the primary antibody for MC4Rs was omitted in the protocol (n = 5). CC, central canal.
The bradycardic responses to microinjections of α-MSH into the nAmb were blocked by prior microinjections of a selective MC4R antagonist at the same site, suggesting that these responses were mediated via MC4Rs in this nucleus. Cyclo[CO-(CH2)2-CO-D-Nal(2′)-Arg-Trp-Lys]-NH2 has been reported to be a selective antagonist for MC4Rs (2). Furthermore, this antagonist did not alter responses to microinjections of an unrelated agonist, L-Glu, into the nAmb. Since microinjections of the antagonist did not elicit significant cardiovascular responses, it was concluded that under normal physiological conditions MC4Rs in the nAmb were not under tonic control of endogenous α-MSH.

The presence of MC4Rs in the nAmb was confirmed by our immunohistochemical studies. There are no immunohistochemical studies on the presence of MC4Rs in the nAmb for comparison of our results. However, in situ hybridization studies have shown the presence of MC4R mRNA in the nAmb (27, 40). The presence of α-MSH-containing fibers in the nAmb has been reported (30). These fibers arise in the hypothalamus and descend in lateral ventrolateral tegmental fiber pathways to the nAmb. The descending fibers decussate in the region encompassing the caudal hypothalamus and rostral midbrain and thereafter project ipsilaterally to the nAmb (11, 15, 30). Activation of these descending pathways may release α-MSH in the nAmb, activate preganglionic parasympathetic neurons, which innervate the heart via the vagus nerves, and elicit bradycardia. Similar α-MSH projections from the hypothalamus to the dorsal vagal nucleus complex have been reported (20).

The majority of cardiac vagal neurons in the nAmb is normally silent, and their firing is controlled by synaptic inputs (45). Major synaptic inputs to cardiac vagal neurons in the nAmb include excitatory glutamatergic pathways from the NTS, excitatory cholinergic inputs that facilitate glutamatergic synaptic pathways innervating these neurons, and inhibitory GABA inputs (44) that may mediate the inhibition of these neurons during inspiration. In our study, microinjections of the MC4R antagonist into the nAmb did not alter reflex bradycardic responses elicited by intravenous infusions of PE, suggesting that α-MSH does not influence the parasympathetic component of baroreflex-induced bradycardia.

It is possible that MC4Rs in nAmb are activated in some pathological conditions. As mentioned in the introduction, α-MSH has been reported to reverse hemorrhagic shock conditions and provide strong protection against myocardial ischemia/reperfusion in experimental animals and humans (9, 10). These effects have been reported to be mediated via MC4Rs in the brain and involve activation of an efferent vagal cholinergic pathway (26). Although this efferent cholinergic pathway has not been characterized, it may involve the nAmb. It is possible that in the aforementioned pathological conditions, α-MSH is released from α-MSH-containing terminals in the nAmb, activating MC4Rs on parasympathetic preganglionic neurons providing innervations to the heart and causing bradycardia.

In summary, microinjections of α-MSH into the nAmb elicit bradycardic responses, which are mediated via MC4Rs. Direct application of α-MSH to nAmb neurons revealed that this peptide excites these neurons via MC4Rs. It was concluded that activation of nAmb neurons caused bradycardia via an increase in vagal activity because bilateral vagotomy abolished the bradycardic effect of α-MSH.

Perspectives and Significance

We hypothesize that in pathological situations such as stress, ischemic stroke and hemorrhagic shock, α-MSH may be released in the nAmb, causing stimulation of parasympathetic preganglionic neurons, efferent vagal activation and consequent bradycardia. Bradycardia can be beneficial in certain situations. For example, electrical vagal stimulation has been used experimentally to prevent ventricular tachycardia and fibrillation during myocardial ischemia/reperfusion (48). Since vagal nerve stimulation has been used for treatment of diseases, such as epilepsy in humans, there is a potential for the use of this procedure to treat pathological situations such as myocardial ischemia/reperfusion injury. An alternative approach for the treatment of these conditions could be to activate pharmacologically a physiologically well-defined vagal cholinergic pathway controlling cardiac function using a relatively safe agent, such as α-MSH. These possibilities remain to be explored.

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