Cerebrospinal Fluid Hypernatremia Elevates Sympathetic Nerve Activity and Blood Pressure via the Rostral Ventrolateral Medulla

Sean D. Stocker, Susan M. Lang, Sarah S. Simmonds, Megan M. Wenner, William B. Farquhar

Abstract—Elevated NaCl concentrations of the cerebrospinal fluid increase sympathetic nerve activity (SNA) in salt-sensitive hypertension. Neurons of the rostral ventrolateral medulla (RVLM) play a pivotal role in the regulation of SNA and receive mono- or polysynaptic inputs from several hypothalamic structures responsive to hypernatremia. Therefore, the present study investigated the contribution of RVLM neurons to the SNA and pressor response to cerebrospinal fluid hypernatremia. Lateral ventricle infusion of 0.15 mol/L, 0.6 mol/L, and 1.0 mol/L NaCl (5 µL/10 minutes) produced concentration-dependent increases in lumbar SNA, adrenal SNA, and arterial blood pressure. Finally, single-unit recordings of spinally projecting RVLM neurons revealed 3 distinct populations based on discharge responses to lateral ventricle infusion of 1 mol/L NaCl. Furthermore, blockade of ionotropic glutamate, but not angiotensin II type 1, receptors significantly attenuated the increase in lumbar SNA, adrenal SNA, and arterial blood pressure. Finally, single-unit recordings of spinally projecting RVLM neurons revealed 3 distinct populations based on discharge responses to lateral ventricle infusion of 1 mol/L NaCl: type I excited (46%; 11/24), type II inhibited (37%; 9/24), and type III no change (17%; 4/24). All neurons with slow conduction velocities were type I cells. Collectively, these findings suggest that acute increases in cerebrospinal fluid NaCl concentrations selectively activate a discrete population of RVLM neurons through glutamate receptor activation to increase SNA and arterial blood pressure. (Hypertension. 2015;66:1184-1190. DOI: 10.1161/HYPERTENSIONAHA.115.05936.) ● Online Data Supplement

Key Words: blood pressure ■ cerebrospinal fluid ■ hypertension ■ hypothalamus ■ sodium

Salt-sensitive hypertension is mediated, in part, by an increase in cerebrospinal fluid (CSF) NaCl concentrations and elevated sympathetic nerve activity (SNA).1,2 Experimental models of salt-sensitive hypertension such as the Dahl salt-sensitive and Spontaneously hypertensive rats are associated with significant increases in lumbar SNA and arterial blood pressure (ABP). To our knowledge, only 1 study is available in salt-resistant humans and has reported that a chronic high-salt diet increased CSF NaCl concentrations and ABP.4,5 The increase in CSF NaCl parallels or even precedes the increase in arterial blood pressure (ABP). Importantly, these changes in CSF NaCl do not occur in salt-resistant counterparts.4,5 However, it is not known whether CSF NaCl of salt-sensitive subjects fluctuate from meal to meal or vary across the circadian cycle. Consistent with the above notion, acute or chronic intracerebroventricular infusion of hypertonic NaCl increases ABP in rodents.7–14 Such responses are enhanced by a high-salt diet12 or exaggerated in salt-sensitive strains such as the Dahl salt-sensitive rat.7,9 Finally, lesion or interruption of neurotransmission in various hypothalamic structures including the PVH and paraventricular nucleus (PVH) attenuates the increase in ABP produced by acute or chronic central infusions of hypertonic NaCl12–14 and also antagonizes the development of salt-sensitive hypertension in several experimental models.15–18 These hypothalamic circuits raise SNA and ABP through a pathway that involves the epithelial sodium channel and ouabain signaling.1,2 Despite evidence for a central NaCl-driven increase in SNA and ABP initiated by the forebrain hypothalamus, the downstream circuitry and signaling mechanisms are unknown. Antunes et al20 reported that acute increases in circulating NaCl concentrations activate a spinal vasopressinergic pathway originating in the PVH. In contrast, salt-sensitive hypertension including the Dahl salt-sensitive rat depends on neurotransmission in the PVH and rostral ventrolateral medulla (RVLM).19,21 RVLM neurons play a pivotal role in the regulation of SNA and ABP during various physiological and.
pathophysiological conditions. These neurons are barosensitive and tonically active and support basal SNA through direct projections to preganglionic neurons of the intermediolateral column cell. Moreover, RVLM neurons receive direct mono- or polysynaptic inputs from several hypothalamic structures activated by hypernatremia. Therefore, these observations prompted us to perform a series of experiments to address the extent by which RVLM neurons mediate changes in ABP and SNA to various end organs during acute increases in CSF NaCl concentration.

Methods
All of the experimental procedures conform to the National Institutes of Health Guide for the Care and Use of Laboratory Animals and were approved by the Institutional Animal Care and Use Committee at the Pennsylvania State College of Medicine. All experiments were performed in male Sprague–Dawley rats (250–400 g; Charles River Laboratories), anesthetized with Inactin (120 mg/kg, IV), and prepared for simultaneous recordings of ABP and SNA (lumbar, renal, splanchnic, and adrenal) as described previously. A brain cannula was implanted into the lateral ventricle for intracerebroventricular infusion of artificial CSF, 0.6 mol/L NaCl, or 1.0 mol/L NaCl (5 µL/10 minutes). The vasopressin antagonist Manning compound (10 µg/kg, IV) was also administered before intracerebroventricular infusions to eliminate the contribution of vasopressin to the NaCl-induced responses. In preliminary experiments, vasopressin receptor blockade attenuated the pressor response by 2±1 mmHg but did not alter SNA responses to intracerebroventricular infusion of 1 mol/L NaCl. A detailed methods section is available in the online only Data Supplement.

Results
There were no differences in baseline mean ABP or heart rate for the various experimental groups (Table S1 in the online only Data Supplement).

Central Components of the NaCl-Induced Pressor Response

Experiment 1
Initial experiments were performed to determine how changes in CSF NaCl concentration altered SNA to various end organs. Intracerebroventricular infusion of 0.15 mol/L, 0.6 mol/L, and 1.0 mol/L NaCl produced concentration-dependent increases in lumbar SNA, adrenal SNA, heart rate, and mean ABP (Figure 1). However, the increase in adrenal SNA and heart rate was delayed and increased ≈8 to 10 minutes after start of the intracerebroventricular infusion. Intracerebroventricular infusion of 1.0 mol/L NaCl decreased renal SNA but did not alter splanchnic SNA. All variables returned to baseline values within 60 minutes (Figure 1).

Experiment 2
In a separate group of animals, CSF was collected from the fourth ventricle to measure changes in Na⁺ and Cl⁻ during infusion of aCSF or 1.0 mol/L NaCl. Infusion of 1.0 mol/L increased fourth ventricular CSF [Na⁺] (baseline, 155.3±0.3 mmol/L versus 15 minutes, 159.0±1.6 mmol/L; n=6; P<0.05) and [Cl⁻] (baseline, 114.6±0.5 mmol/L versus 15 minutes, 118.6±0.7 mmol/L; n=6; P<0.05). Infusion of 0.15 mol/L CSF did not alter CSF [Na⁺] (baseline, 155.7±0.3 mmol/L versus 15 minutes, 155.0±0.6 mmol/L; n=6; P<0.05) and [Cl⁻] (baseline, 116.7±0.3 mmol/L versus 15 minutes, 117.0±0.2 mmol/L; n=6; P>0.05).

Experiment 3
To assess the contribution of elevated SNA to the NaCl-induced pressor responses, intracerebroventricular infusions were performed after ganglionic blockade. Intravenous injection of chlorisondamine promptly decreased baseline SNA and mean ABP and abolished the SNA, tachycardic, and pressor response to 0.6 mol/L and 1.0 mol/L NaCl (Figure 2).

Experiment 4
To demonstrate that these SNA responses depend on the lamina terminalis, intracerebroventricular infusions were performed in a fourth set of animals with acute electrolytic lesion of the AV3V. AV3V lesions significantly attenuated the increase in lumbar SNA, adrenal SNA, mean ABP, and heart rate to infusion of 0.6 mol/L and 1.0 mol/L NaCl (Figure 3; Figure S2 for histology). The lesion also significantly attenuated the renal sympathoinhibitory response to 0.6 mol/L and 1.0 mol/L NaCl.

RVLM Neurons Mediate Sympathoexcitatory and Pressor Responses to Intracerebroventricular NaCl

Experiment 5
To test whether RVLM neurons mediate the sympathoexcitatory response to CSF NaCl, intracerebroventricular infusions were performed after inhibition of the RVLM. Bilateral injection of the GABA antagonist muscimol promptly reduced lumbar SNA (−76±6%; P<0.01), renal SNA (−53±10%; P<0.01), adrenal SNA (−62±6%; P<0.01), splanchnic SNA (−35±9%; P<0.01), mean ABP (88±5–57±7 mmHg; P<0.01), and heart rate (405±12–365±19 bpm; P<0.01). Importantly, bilateral injection of muscimol abolished the lumbar sympathoexcitatory and pressor response to intracerebroventricular infusion of 1.0 mol/L NaCl (Figure 4). The adrenal sympathoexcitatory response was partially attenuated. Bilateral injection of aCSF into the RVLM did not significantly alter any baseline variable (data not shown) or alter the responses to intracerebroventricular infusion of NaCl (Figure 4).

Experiment 6
To identify the neurotransmitter receptor in the RVLM that mediates the above responses, intracerebroventricular infusions were performed after blockade of ionotropic glutamate or angiotensin type 1 receptors in the RVLM. Bilateral injection of kynurenic acid into the RVLM produced a small reduction in lumbar SNA (−6±1%; P<0.05) but did not alter renal SNA (−4±5%; P>0.01), adrenal SNA (−4±7%; P>0.05), splanchnic SNA (−1±1%; P>0.05), mean ABP (85±5–84±4 mmHg; P>0.05), and heart rate (350±18–346±13 bpm; P>0.05). Blockade of RVLM glutamate receptors with kynurenic acid significantly attenuated the increase in lumbar SNA, adrenal SNA, heart rate, and mean ABP to intracerebroventricular infusion of 1.0 mol/L NaCl (Figure 5). In addition, kynurenic acid also reduced the renal sympathoinhibitory response. In contrast, bilateral injection of the angiotensin type 1 receptor antagonist losartan did not alter the sympathetic, tachycardic, and pressor responses to intracerebroventricular infusion of 1.0 mol/L NaCl (Figure 5). RVLM injection of losartan did not alter baseline lumbar SNA (10±7%; P>0.05), renal SNA (2±3%; P>0.05), adrenal SNA (−1±3%; P>0.05), splanchnic...
SNA (3±2%; P>0.05), mean ABP (90±4 to 92±5 mmHg; P>0.05), and heart rate (371±15 to 368±14 bpm; P>0.05).

CSF Hypernatremia Differentially Affects the Discharge of RVLM Neurons

Experiment 7

A final set of experiments was performed to establish that CSF hypernatremia alters the activity of barosensitive, spinally projecting RVLM neurons. Neurons were divided into 3 types based on the discharge responses to intracerebroventricular infusion of 1 mol/L NaCl. Type I neurons (11/24; 46%) had a baseline discharge of 11±2 Hz and conduction velocity of 2.1±0.4 m/s. Intracerebroventricular infusion of 1.0 mol/L NaCl increased cell discharge within 2 minutes after onset of the infusion, and the activity remained elevated throughout the infusion despite an increased mean ABP (Figure 6). Type II neurons (9/24; 37%) had a baseline discharge and conduction velocity of 11±3 Hz and 2.6±0.3 m/s, respectively. However, infusion of 1 mol/L NaCl decreased the discharge rate of these neurons at 4 minutes after the onset of the intracerebroventricular infusion (Figure 6; Figure S3). Type III neurons (4/24; 17%) displayed a baseline discharge and conduction velocity of 17±8 Hz and 2.3±0.5 m/s, respectively. Infusion of 1 mol/L NaCl did not alter discharge rate in these neurons (Figure 6; Figure S4). A previous study suggested that RVLM neurons may be distinguished between C1 and non-C1 cells based on the conduction velocity because slowly conducting neurons (<1 m/s) were consistently identified as C1 neurons. Therefore, we performed a retrospective analysis of RVLM neurons and the respective conduction velocities using a criteria of <1 m/s to identify putative C1 neurons. This analysis identified 4 RVLM neurons with a conduction velocity of 0.8±0.1 m/s and baseline discharge rate of 7.5±3.0 Hz. Interestingly, all 4 neurons displayed an increased discharge response to intracerebroventricular infusion of 1 mol/L NaCl (Figure 6).

Discussion

Previous studies have documented that increased CSF [Na+] elevates ABP, but the neural pathways and contribution of RVLM neurons have not been determined previously. The present findings provide several novel observations: (1) acute intracerebroventricular infusion of NaCl differentially increases lumbar and adrenal SNA, decreases renal SNA, and does not change splanchnic SNA, (2) acute AV3V lesion prevents these changes, (3) inhibition of RVLM neurons with the GABAA agonist muscimol or blockade of RVLM ionotropic glutamate receptors significantly attenuates the sympathetic and ABP responses to intracerebroventricular infusion of hypertonic NaCl, and (4) acute intracerebroventricular infusion of hypertonic NaCl differentially affected the discharge frequency of RVLM neurons.
spinally projecting RVLM neurons. Collectively, these findings suggest that the sympathoexcitatory response to CSF hypernatremia depends on AV3V neurons to increase glutamatergic drive onto a selective population of RVLM neurons.

Plasma or CSF hypernatremia increases SNA and ABP in both rodents and humans. However, the sympathoexcitatory response is likely end-organ dependent. Indeed, our current findings document, for the first time, that acute intracerebroventricular infusion of hypertonic NaCl produced a differential activation of lumbar and adrenal SNA but inhibition of renal SNA and no change in splanchnic SNA. In agreement, several studies have acutely raised NaCl concentrations in different species and through different routes to produce qualitatively similar responses and include (1) intravenous infusion in rodents produce a similar differential SNA response, intracarotid infusion of NaCl to produce physiological changes decreases renal SNA, and (3) intravenous infusion in humans increases muscle SNA. This SNA pattern may promote increased sodium excretion through a pressure-natriuresis mechanism and concurrent inhibition of renal SNA through a direct Na+-sympathoinhibitory pathway or a baroreceptor-mediated inhibition of RVLM discharge. The latter may be particularly evident under Inactin-anesthesia; however, unpublished findings in our laboratory indicate a similar pattern of SNA to intracerebroventricular infusion of hypertonic NaCl across several anesthetics (urethane, chloralose, and isoflurane). The elevated SNA is significant because the pressor response was prevented by the ganglionic blocker chlorisondamine. In contrast, other studies have reported that intracerebroventricular infusion of hypertonic NaCl increases renal SNA. Although our studies were performed in anesthetized animals, the above-referenced renal SNA recordings were performed within a few hours of surgery and implantation of the renal nerve electrodes. Second, the infusion volumes into the lateral ventricle was much larger in those studies (30–40 µL in 8–10 minutes) versus the current experiments (5 µL in 10 minutes). Although the intracerebroventricular infusion of 1 mol/L NaCl increased CSF [Na+] and [Cl⁻] in the fourth ventricle by 2 to 4 mmol/L, the changes are likely greater in the hypothalamus. Clearly, additional studies are needed in which chronic SNA recordings across different end organs during intracerebroventricular infusion of hypertonic NaCl or in salt-sensitive models associated with elevated CSF NaCl concentration.

The forebrain lamina terminalis is a pivotal site for the interaction between NaCl and SNA. A V3V lesions blunt osmotically dependent responses including thirst, vasopressin secretion, and natriuresis. These same lesions attenuate or reverse several experimental models of salt-sensitive

Figure 3. A, Arterial blood pressure (ABP); mean ABP (gray line); and lumbar, adrenal, and renal sympathetic nerve activity (SNA) during intracerebroventricular (ICV) infusion of artificial cerebrospinal fluid (aCSF) or 1.0 mol/L NaCl in AV3V-lesioned rat. B, Mean±SEM peak changes of control and AV3V-lesioned animals during ICV infusion of aCSF, 0.6 mol/L NaCl, and 1.0 mol/L NaCl. *P<0.05 vs control, #P<0.05 between NaCl concentrations (aCSF vs 0.6 mol/L vs 1.0 mol/L). rSNA indicates raw SNA.

Figure 4. A, Arterial blood pressure (ABP); mean ABP (gray line); and lumbar, adrenal, and renal sympathetic nerve activity (SNA) during intracerebroventricular (ICV) infusion of 1.0 mol/L NaCl after bilateral rostral ventrolateral medulla (RVLM) injection of artificial cerebrospinal fluid (aCSF) or the GABA agonist muscimol. B, Mean±SEM peak changes and schematic illustration of RVLM injection sites. *P<0.05 vs 0.15 mol/L NaCl, #P<0.05, aCSF vs muscimol. HR indicates heart rate; and rSNA, raw SNA.
Hypertension.

Our findings extend these observations and demonstrate that both sympathoexcitatory (lumbar and adrenal) and sympathoinhbitory (renal) responses to increased CSF [NaCl] are prevented by AV3V lesions. The manner by which AV3V neurons contribute to these responses likely reflect a Na+-specific versus osmosensitive mechanism as intracerebroventricular or intracarotid infusions of NaCl versus other solutes produce greater increases in SNA or ABP.10,35,41 In this regard, Blaustein et al2 have postulated that NaCl activates an epithelial sodium channel-ouabain pathway in the hypothalamus to increase SNA and ABP; however, future studies are needed to directly link this signaling pathway to excitatory responses of Na+-sensing neurons to hypertonic NaCl.

A major goal of these experiments was to identify whether RVLM neurons contribute to the sympathetic and pressor effects of central hypernatremia. Indeed, our findings demonstrate that inhibition of RVLM neurons or blockade of ionotropic glutamate receptors on RVLM neurons prevents or attenuates, respectively, the sympathetic and pressor responses to intracerebroventricular NaCl. Interestingly, blockade of glutamate receptors in the RVLM lowers ABP in Dahl salt-sensitive rats.21 Although we did not identify the origin of glutamatergic drive to the RVLM, it likely involves a polysynaptic pathway from the AV3V region as injection of retrograde tracers into the RVLM does not produce robust labeling in these nuclei.22,42 Although all sources of glutamatergic drive to the RVLM have not been identified, the majority of PVH neurons projecting to the RVLM express vesicular glutamate transporter-2 mRNA, a marker of glutamatergic neurons.27 Furthermore, the PVH contributes to the sympathetic and pressor responses to acute intracerebroventricular NaCl infusions and elevated ABP in Dahl salt-sensitive rats.17,18,21 Altogether, these findings suggest that central hypernatremia activates hypothalamic pathways to increase glutamatergic drive onto RVLM neurons to increase SNA and ABP in salt-sensitive hypertension.

The single-unit recordings of RVLM neurons demonstrate 3 populations distinguished by the discharge response to intracerebroventricular infusion of NaCl. Approximately one half of these neurons increased discharge to central NaCl infusion, a response consistent with the increase in lumbar and adrenal SNA. The other populations (types II and III) may reflect neurons that regulate renal and splanchnic SNA, respectively. It is unclear whether the discharge responses reflect the integration of glutamatergic, GABAergic, and other synaptic inputs.
at the level of RVLM versus a selective increase in gluta-
materic drive onto RVLM neurons regulating lumbar and adre-
nal SNA. Finally, RVLM neurons have been neurochemically
distinguished by the presence or absence of PNMT and con-
sidered C1 versus non-C1 neurons, respectively. A previous
electrophysiological study reported that all neurons with a
conduction velocity <1 m/s were C1 neurons. Here, a ret-
rospective analysis identified 4 neurons with a conduction
velocity <1 m/s, and all 4 neurons displayed an increase in
discharge during intracerebroventricular infusion of hyper-
tonic NaCl. Although the immunocytochemical processing
for tyrosine hydroxylase in our study was unsuccessful, these
findings raise the interesting possibility that increased CSF
NaCl concentrations may increase SNA and ABP through a
selective activation of C1 neurons in the RVLM.

The current study used an acute intracerebroventricular infu-
sion of hypertonic NaCl to gain insight into the pathways and
mechanisms that may be activated in salt-sensitive hypertension.
A clinical study and various experimental animal models have
reported that a high-salt diet increases CSF Na+ concentra-
tions in salt-sensitive subjects or animals but not in salt-resistant
counterparts. Evidence suggests that a tonic activation of fore-
brain Na+ sensitive mechanisms persist in salt-sensitive hyper-
tension as acute intracarotid infusion of hypertonic fluid lowers
SNA and ABP in DOCA-salt hypertension rats. However, there are
likely additional neuroplastic changes that occur during
chronic increases in CSF Na+ concentrations or dietary salt
intake to further elevate SNA and ABP. For example, a high-salt
diet exaggerates SNA and ABP responses of Sprague–Dawley,
Dahl salt-resistant, and Dahl salt-sensitive rats to various stimuli
including subsequent intracerebroventricular infusion of hyper-
tonic NaCl, thereby suggesting that salt sensitizes central
sympathetic networks. Independent of salt intake, salt-sensitive
individuals and animal strains display exaggerated SNA and
ABP responses to various stressors or activation of RVLM
neurons. Additional studies are needed to investigate whether
these differences reflect altered neuronal function within dis-
crete populations of RVLM neurons that are affected by acute or
chronic changes in CSF [Na+] or dietary salt.

Perspectives
Salt-sensitive hypertension is mediated, in part, by elevated
SNA driven by a central hypernatremia. The present findings
highlight the accumulating evidence for the ability of the cen-
tral nervous system to differentially control SNA and end-organ
function. Such control mechanisms have important implications
for nerve denervation studies. For example, acute intracerebro-
ventricular infusion of hypertonic NaCl decreased renal SNA.
Moreover, renal denervation has little effect on the development
of hypertension in salt-sensitive models associated with a cen-
tral hypernatremia (ie, Dahl salt-sensitive rat). In addition, the
findings also highlight the presence of distinct population
of neurons in the RVLM that provide the cellular basis for the
differential control of SNA. The identity and cellular phenotype
of these cells may represent a future therapeutic target for the
treatment of salt-sensitive hypertension.

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Disclosures
None.

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Novelty and Significance

What Is New?

• An acute increase in cerebrospinal fluid NaCl concentration elevates lumbar and adrenal sympathetic nerve activity, decreases renal sympathetic nerve activity, and does not affect splanchnic sympathetic nerve activity.
• The sympathoexcitatory response depends on glutamatergic receptor activation in the rostral ventrolateral medulla (RVLM).
• Acute intracerebroventricular infusion of hypertonic NaCl differentially affects the activity of bulbospinal RVLM neurons including an increased discharge frequency.
• Every slowly conducting RVLM neuron (<1 m/s) displayed an increased firing rate to intracerebroventricular infusion of hypertonic NaCl.
• The sympathetic control of blood pressure.
• The findings suggest that acute increases in cerebrospinal fluid NaCl concentrations differentially alter sympathetic outflow to increase arterial blood pressure.
• The sympathetic and pressor responses depend on glutamatergic inputs onto a select population of RVLM neurons.

What Is Relevant?

• Increased cerebrospinal fluid NaCl concentrations differentially alter sympathetic outflow to increase arterial blood pressure.
• The sympathetic and pressor responses depend on glutamatergic inputs onto a select population of RVLM neurons.

Summary

The findings suggest that acute increases in cerebrospinal fluid NaCl concentrations differentially elevate sympathetic nerve activity and ABP through increased glutamatergic inputs onto bulbospinal RVLM neurons that originates from the AV3V region.
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CSF Hypernatremia Elevates Sympathetic Nerve Activity and Blood Pressure

via the Rostral Ventrolateral Medulla

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METHODS

Animals. All of the experimental procedures conform to the National Institutes of Health Guide for the Care and Use of Laboratory Animals and were approved by the Institutional Animal Care and Use Committee at the Pennsylvania State College of Medicine. Male Sprague-Dawley rats (250-400 g, Charles River Laboratories) were housed in a temperature-controlled room (22±1°C) with a 12-hour light-dark cycle. Rats were fed standard chow (Harlan Teklad Global Diet 2018) and given access to deionized water.

General Procedures. Rats were anesthetized with isoflurane (2-3% in 100% O2) and prepared for simultaneous recordings of ABP and SNA (lumbar, renal, splanchnic, and adrenal) as described previously. Animals were artificially ventilated with oxygen-enriched room air. End-tidal CO2 and body temperature were maintained at 3.5-4.5% and 37±0.5°C, respectively. Rats were placed into a stereotaxic head frame, and a brain cannula was implanted into the lateral ventricle for intracerebroventricular (ICV) infusions using coordinates in reference to Bregma: -1.5 mm caudal, 1.5-1.7 mm lateral, and -4.5 below the skull. After all surgical procedures were complete, anesthesia was replaced by Inactin (120 mg/kg, IV). Animals also received a continuous infusion of 0.75% NaCl and 0.25% glucose (0.5mL/hr, IV). The level of anesthesia was monitored by the lack of a withdrawal reflex (without neuromuscular blockade) or the pressor response (during neuromuscular blockade) to a foot pinch. The surgery was performed over 1-2 hours. Variables were allowed to stabilize for 1 hr. At the end of experiments, animals were perfused transcardially with 4% paraformaldehyde. Placement of brain cannulas was verified by presence of dye in the 3rd and 4th ventricle after injection of Evan’s Blue Dye (0.5%, 2µL).

Central Components of NaCl-Induced Pressor Response.

Experiment 1. An initial set of experiments was performed to quantitatively determine the changes in SNA to various end-organs during increases in CSF NaCl concentration (see Figure S1). Animals were prepared as described above and pretreated with the vasopressin receptor antagonist Manning compound (10µg/kg, IV) to eliminate the contribution of vasopressin to the NaCl-induced pressor response. In preliminary experiments, vasopressin receptor blockade attenuated the pressor response by 2±1 mmHg but did not alter sympathetic nerve activity to ICV infusion of NaCl. Approximately ~5-10 min later, 0.15M, 0.6M, or 1.0M NaCl (5µL/10min) was infused ICV. Variables were recorded for an additional 60 min. Each concentration was tested once per animal separated by a minimum of 60 min after variables returned to baseline values.

Experiment 2. In a separate set of animals, CSF was collected from the 4th ventricle to measure the resultant changes in CSF Na+ and Cl− concentrations. Animals
were prepared as described above, and the muscle overlying the atlanto-occipital bone and hindbrain were removed. CSF was collected by applying negative pressure to a 27 gauge needle and 1cc syringe inserted into the 4th ventricle through the dura without physical damage to the dorsal surface of the medulla. CSF was collected at 15 min after start of the 0.15M and 1.0M NaCl ICV infusion. This time point was selected based on preliminary experiments to indicate that peak changes were observed at 15 min but not 5 or 25 min. Electrolytes were measured using an I-STAT and 6+ cartridges.

**Experiment 3.** In a third set of animals, the contribution of the sympathetic nervous system to the NaCl-induced pressor response was assessed in rats pretreated with the ganglionic blocker chlorisondamine. Animals were prepared as described above. Then, the ganglionic blocker chlorisondamine (5mg/kg, IV) was administered. Approximately 5-10 later when variables stabilized, ICV infusion of 0.15M, 0.6M, and 1.0M NaCl were performed as described above.

**Experiment 4.** In a fourth group of animals, we evaluated the contribution of the AV3V region to the changes in SNA and ABP during acute elevation in CSF NaCl concentrations. Animals were prepared as described above. In addition, a small craniotomy was performed to gain access to the overlying cortex and midsagittal sinus dorsal to the AV3V region. Then, electrolytic lesion of the AV3V was performed as previously described in our laboratory. Briefly, a Teflon-coated tungsten electrode (250-µm tip, 0.008 OD, AM Systems) angled 8° from the midsagittal plane was lowered into the ventral LT using coordinates in reference to bregma: 0.0- to 0.5-mm rostral, 1.0-mm lateral, and 8.0-mm ventral to dura. DC current (500 µA) was applied for 30 seconds. Approximately 1 hr later, ICV infusions of NaCl were performed as described above.

**Contribution of RVLM Neurons to NaCl-Induced Sympathoexcitation and Pressor Response.** Additional experiments were performed to assess the contribution of RVLM neurotransmission to the changes in SNA and ABP during acute elevation in CSF NaCl concentrations. Animals were prepared as described above. Then, the RVLM was localized bilaterally by field potential recordings of the facial nucleus during electrical stimulation of the mandibular branch of the facial nerve (0.2 ms, 500µA, 1Hz) using glass pipettes (20-30µm diameter, one for each side) filled with aCSF as described previously. RVLM injections were performed 200µm caudal, 200 µm medial, and 200µm deeper than the ventral and caudal pole of the facial nucleus. All injections (60nL) were performed over 10 s using a pneumatic picopump. Injection sites were marked by the addition of rhodamine or FITC beads (0.2%) to all solutions.

**Experiment 5.** To test whether RVLM neurons mediate the sympathoexcitatory response to ICV infusion of NaCl, the GABA_A receptor agonist muscimol (2mM) was injected bilaterally separated by <1 min. Approximately 15 min later when variables stabilized, 0.15M or 1.0M NaCl was infused ICV (5µL/10 min) as described above. Variables were recorded for an additional 60 min. Then, the RVLM injection was repeated to infuse the other ICV solution.
**Experiment 6.** To identify the receptor in RVLM that mediates the sympathoexcitatory response to ICV infusion of NaCl, additional groups of animals received a bilateral RVLM injection of the ionotropic glutamate receptor antagonist kynurenic acid (40mM) or the AT1R antagonist losartan (1mM). These doses have been justified previously. At 5 min later, 0.15M or 1.0M NaCl was infused ICV as described above in a randomized order. At 1 hr later, the RVLM injection was repeated to infuse the other ICV solution. Control experiments injected aCSF into the RVLM bilaterally. Only 1-2 drugs were tested per animal.

**Single-Unit Recording of RVLM Neurons.**

**Experiment 7.** A final set of experiments was performed to assess the changes in RVLM neuronal activity during ICV infusion of NaCl. Another set of animals were prepared as described above. Single-unit recordings were performed in a final set of animals using a transcerebellar approach and glass electrodes (10-20MΩ) filled with 3% biotinamide in 0.5% sodium acetate. Briefly, a craniotomy was performed to gain access to the cerebellum overlying the medulla. The RVLM was localized by facial field potential recordings as described in Experiments 5 and 6. In addition, a laminectomy was performed to insert a stimulating electrode into the dorsolateral funiculus for antidromic identification of RVLM neurons. Spinally-projecting RVLM neurons were identified using antidromic stimulation (0.5-1s duration, 1Hz, 0.5-1mA) from the T2 spinal segment using a bipolar electrode after animals received pancuronium (0.5-1.0 mg/kg, IV). Units were deemed antidromic according to the following criteria: 1) constant onset latency, 2) ability to follow high frequency stimulation (>250Hz), and 3) collision of an antidromic and spontaneous spike. In addition, RVLM neurons were also tested for barosensitivity using a brief increase in aortic blood pressure (10-20 s) produced by an aortic cuff placed around the aorta proximal to the renal vessels.

Once a barosensitive, spinally-projecting RVLM unit was identified, animals were treated with the vasopressin antagonist and infused ICV with 0.15M or 1M NaCl as described above. At the end of experiments, cells were juxtacellularly labeled by applying current steps (400 ms, 50% duty cycle, 1-8nA) through the recording electrode or the recording site was marked by applying DC current (50μA, 30 s). Then, the animals was perfused transcardially with 4% paraformaldehyde, post-fixed in 4% paraformaldehyde for 1-2 days, and sectioned at 50μm using a vibratome. Juxtacellularly labeled cells (or recording sites) were visualized by an overnight incubation with streptavidin AlexaFluor 594.

**Statistical Analysis.** All data are expressed as mean±SEM. Changes in SNA were calculated by subtracting background noise after physically crushing the nerve. SNA and ABP were averaged over 1 min bins and compared to an average baseline period (10 min). All data were analyzed by one- or two-way ANOVA with repeated measures when appropriate (Systat 10.2). Normal distribution was verified for all data sets by
skewness (<±2) and kurtosis measurements (<±2). All post hoc tests were performed using independent or paired t-tests with a layered Bonferroni correction. P values <0.05 were considered statistically significant.
REFERENCES


Table S1. Baseline mean ABP and heart rate for various experimental groups.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mean ABP (mmHg)</th>
<th>Heart Rate (bpm)</th>
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<tbody>
<tr>
<td><strong>Dose-Response</strong> (Figure 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>aCSF</td>
<td>93±3</td>
<td>383±8</td>
</tr>
<tr>
<td>0.6M NaCl</td>
<td>91±3</td>
<td>388±9</td>
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<tr>
<td>1.0M NaCl</td>
<td>91±3</td>
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<td><strong>Ganglionic Blockade</strong> (Figure 2)</td>
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<td>Pre-Treatment</td>
<td>105±8</td>
<td>362±8</td>
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<tr>
<td>Post-Treatment</td>
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<td></td>
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<tr>
<td>aCSF</td>
<td>63±4</td>
<td>340±8</td>
</tr>
<tr>
<td>0.6M NaCl</td>
<td>61±4</td>
<td>346±6</td>
</tr>
<tr>
<td>1.0M NaCl</td>
<td>63±5</td>
<td>346±9</td>
</tr>
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<td><strong>AV3V lesion</strong> (Figure 3)</td>
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<td>aCSF</td>
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<tr>
<td>0.6M NaCl</td>
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<td>397±14</td>
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<tr>
<td>1.0M NaCl</td>
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<td><strong>RVLM Microinjection</strong> (Figures 4 and 5)</td>
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<tr>
<td>aCSF</td>
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<tr>
<td>Muscimol</td>
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<td>Kynurenic Acid</td>
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<td>Losartan</td>
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<td><strong>RVLM Cell Recordings</strong> (Figure 6)</td>
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<tr>
<td>Type I Neurons</td>
<td>94±4</td>
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<tr>
<td>Type II Neurons</td>
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<tr>
<td>Type III Neurons</td>
<td>93±5</td>
<td>443±10</td>
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</table>

Values are mean±SEM.
Figure S1. General protocol for the experiments designed to test the changes in SNA and ABP during ICV infusion of 0.15M, 0.6M, and 1.0M NaCl. After a 2 hr surgery and 1 hr stabilization, the experimental protocol consisted of a 10 min baseline recording and IV administration of Manning Compound to block vasopressin receptors. Once variables stabilized 5-10 min later, ICV infusion of 0.15M, 0.6M, and 1.0M NaCl was performed in a randomized order. Variables were recorded for an additional 60 min. Then, the ICV infusion protocol was repeated in the same animal but a different concentration of NaCl was infused.

**Experiment 1.** The experimental protocol was performed as outlined in Figure S1.

**Experiment 2.** CSF samples were collected from the 4th ventricle at 15 min after start of the ICV infusion. Only 1 infusion was tested per animal.

**Experiment 3.** The ganglionic blocker was administered once immediately after the Manning Compound.

**Experiment 4.** Electrolytic lesion of AV3V was performed at the end of surgery period.

**Experiments 5 and 6.** RVLM injection of muscimol or aCSF was performed immediately after the IV injection of Manning Compound.

**Experiment 7.** Once an RVLM neuron was identified, Manning Compound was administered IV and neuronal responses to ICV infusion of 0.15M or 1.0M NaCl were recorded.
Figure S2. (A) Schematic illustration of AV3V lesions and (B) Digital images of control and AV3V-lesioned animals (Scale bar = 500 µm). The lesion boundary is outlined in black of shades of grey. Coordinates are in reference to Bregma. Abbreviations: LV, lateral ventricle; DBB, diagonal band; AC, anterior commissure; OVLT, organum vasculosum of the lamina terminalis; MnPO, median preoptic nucleus; 3V, 3\textsuperscript{rd} ventricle; OC, optic chiasm; f, fornix; SFO, subfornical organ; PVH, hypothalamic paraventricular nucleus.
Figure S3. (A, i) Example of ABP, renal SNA, and cell discharge of a Type II RVLM neuron during ICV infusion of 1M NaCl. Type II neurons were antidromically activated from the spinal cord (ii) and barosensitive (iii). △, spontaneous spike; ▼, antidromic spike; *stimulus artifact. Summary data presented in Figure 6.
Figure S4. (A, i) Example of ABP, splanchnic SNA, and cell discharge of a Type III RVLM neuron during ICV infusion of 1M NaCl. Type III neurons were antidromically activated from the spinal cord (ii) and barosensitive (iii). △, spontaneous spike; ▽, antidromic spike; *stimulus artifact. Summary data presented in Figure 6.