*Am J Physiol Regul Integr Comp Physiol* 299: R405–R415, 2010.
First published May 12, 2010; doi:10.1152/ajpregu.00103.2010.



# Circulating signals as critical regulators of autonomic state—central roles for the subfornical organ

**Pauline M. Smith and Alastair V. Ferguson**

*Department of Physiology, Queen's University, Kingston, Ontario, Canada*

Submitted 9 February 2010; accepted in final form 6 May 2010

**Smith PM, Ferguson AV.** Circulating signals as critical regulators of autonomic state—central roles for the subfornical organ. *Am J Physiol Regul Integr Comp Physiol* 299: R405–R415, 2010. First published May 12, 2010; zdoi; 10.1152/ajpregu.00103.2010.—To maintain homeostasis autonomic control centers in the hypothalamus and medulla must respond appropriately to both external and internal stimuli. Although protected behind the blood-brain barrier, neurons in these autonomic control centers are known to be influenced by changing levels of important signaling molecules in the systemic circulation (e.g., osmolarity, glucose concentrations, and regulatory peptides). The subfornical organ belongs to a group of specialized central nervous system structures, the circumventricular organs, which are characterized by the lack of the normal blood-brain barrier, such that circulating lipophobic substances may act on neurons within this region and via well-documented efferent neural projections to hypothalamic autonomic control centers, influence autonomic function. This review focuses on the role of the subfornical organ in sensing peripheral signals and transmitting this information to autonomic control centers in the hypothalamus.

autonomic; cardiovascular; satiety signals; immune regulation; blood-brain barrier

TO MAINTAIN HOMEOSTASIS, autonomic control centers in the hypothalamus and medulla must respond appropriately to both external and internal stimuli. It is well established that mechanisms exist for the relay of essential information derived in the periphery, detected by specialized sensory structures (i.e., baroreceptors, chemoreceptors), to hypothalamic and medullary autonomic nuclei through afferent neural inputs. It is also known that the activity patterns (i.e., outputs) of neurons in these autonomic control centers are influenced by changing levels of important signaling molecules in the systemic circulation (e.g., osmolarity, glucose concentrations, and regulatory peptides), despite the fact that all of the important hypothalamic and medullary autonomic control centers are protected from direct access to such circulating autonomic signals by the blood-brain barrier (BBB).

The anatomical features of the BBB are well understood. The BBB consists not only of endothelial cells of cerebral microvessels joined together by tight junctions (in strict contrast to the fenestrations between endothelial cells in most capillaries), but also astrocytes, the end feet of which wrap around the brain side of the endothelial cell membrane (1). The tight junctions of the endothelial cells are more complex in the central nervous system (CNS) than in the periphery, in that there are networks of strands formed by intramembranous particles joining adjacent cells (140). The continuity of the BBB ensures that all transport occurs across the cell membrane, thus limiting movement across the barrier to substances that are either lipophilic (and thus readily diffusible across the lipid bilayer), or substances that are transported across this barrier by alternative mechanisms. The existence of the BBB thus means that nearly all large hydrophilic molecules, such as peptides and proteins, which do not have a specific transport system, are excluded from the CNS. The barrier develops during late prenatal and early postnatal life and importantly has been shown to be compromised in a number of pathological states, including inflammation and hypertension (1).

In this way, the BBB allows preferential maintenance of the constituents of the extracellular fluid of the brain in a number of important ways. Perhaps most importantly, the BBB ensures that potential "toxins" in the circulation do not access CNS tissue and compromise CNS function. Secondly, by effectively creating a separate brain fluid compartment, the BBB permits the use of chemical messengers used in the circulation as hormones to also be used behind the BBB as chemical messengers (neurotransmitters/neuromodulators) in neuron-to-neuron communication within the CNS. This compartmentalization effectively precludes autonomic control centers within the CNS from directly monitoring the varying levels of many of these important peripheral indicators of physiological status as such peripheral access would effectively "short-circuit" neurotransmitter function of the same signaling molecule.

As suggested above, there is now a clear understanding that neurons in both medullary and hypothalamic autonomic control centers must receive information provided by these peripheral signals, many of which cannot diffuse across the BBB, to accurately assess the global state of the "milieu interieur." The recognition that this occurs leads to the critical question of "How do CNS structures, protected behind the BBB, sense circulating signals, which do not cross the BBB?"

Address for reprint requests and other correspondence: A. V. Ferguson, Dept. of Physiology, Queen's Univ., Kingston, Ontario, Canada K7L 3N6 (e-mail: avf@queensu.ca).

There are at least five primary mechanisms through which transfer of information might occur:

- The vagus nerve can transmit information from the periphery to the CNS through access points in the medulla.
- Lipophilic substances can readily pass through the lipid bilayer of the cell membrane (e.g., steroids, barbiturates, and alcohol) by simple diffusion through the endothelial cell membranes of the cerebral vasculature to access neural tissue behind the BBB.
- Specific saturable transporters may move lipophobic substances (e.g., glucose, leptin, and cytokines) across the barrier (6).
- Signaling molecules may act on one side of the endothelial cell and, by transendothelial cell signaling, induce release of a second molecule on the other side of the barrier (89).
- Circulating lipophobic substances may act on neurons in specialized regions of the brain known as the circumventricular organs (CVOs), which lack the normal BBB (contain fenestrated capillaries).

This latter possibility, and, in particular, the role of one of these CVOs—the subfornical organ (SFO)—in sensing such peripheral signals and transmitting this information to autonomic control centers in the hypothalamus will be the focus of the remainder of this review.

### *Specialized Anatomical Features of the CVOs*

The fenestrated capillaries of the CVOs are distinct from the rest of the CNS (43) in that they lack the typical tight junctions between adjacent endothelial cells (91). In addition, the CVOs possess an extensive and complex vascular supply compared with other areas of the brain, which includes capillary loops extending to the ependymal surface and large, perivascular spaces (Virchow-Robin spaces) surrounding the blood vessels (42), characteristics that maximize the time and area for exposure of blood-borne substances to the cellular components of the CVOs (42). In addition to the lack of the normal BBB and the dense vascular supply, the sensory CVOs (SFO, organum vasculosum of the lamina terminalis, and the area postrema) contain exceptionally dense aggregations of a variety of different receptors for peripheral signals, including regulatory peptides (e.g., angiotensin, cholecystokinin, ghrelin, leptin) (78, 93, 115, 122), steroids (e.g., estradiol) (102), and specific ions (e.g., $Ca^{2+}$, $Na^{+}$) (85, 100), observations that clearly suggest the ability of neurons in these CVOs to sense circulating concentrations of these signaling molecules. These specialized anatomical features uniquely position the sensory CVOs with the potential to directly monitor the constituents of peripheral circulation and communicate this information, via well-documented afferent projections, to autonomic control centers in the hypothalamus and medulla. The sensory CVOs thus represent potential windows in the brain for autonomic feedback to the CNS.

### *SFO*

One such specialized CNS structure is the SFO, located in the forebrain on the midline wall of the third ventricle. It consists primarily of neuronal cell bodies, which receive afferent input from the circulation and communicate this information, via well-documented efferent neural projections (see *Anatomical Features of the SFO*), to hypothalamic autonomic control centers.

### *Anatomical Features of the SFO*

The SFO comprises two distinct regions (a core region and peripheral outer zone) with differing neuronal projections and ligand binding abilities (74). The SFO sends both direct (monosynaptic) and indirect (polysynaptic) efferent projections to the hypothalamic autonomic control and neuroendocrine centers, such as the paraventricular (PVN) and supraoptic nuclei (SON) (71, 79), respectively. Specific excitatory projections have been found in vasopressin- and oxytocin-secreting magnocellular neurons in the SON and PVN, as well as in parvocellular areas of the PVN, which, in turn, project either to the median eminence, the medulla, or the spinal cord (for review, see Ref. 30).

The SFO also sends efferents to neurons in the anteroventral third ventricle region, specifically to the median preoptic nucleus and to the organum vasculosum of the lamina terminalis (71, 80), both of which, in turn, send additional axonal projections to hypothalamic centers, including SON and PVN (80). Less dense efferent connections from the SFO to the zona incerta, raphé nuclei, infralimbic cortex, rostral and ventral portions of the bed nucleus of the stria terminalis, lateral preoptic area, and lateral hypothalamus/dorsal perifornical region have been reported (68, 79), while one study has suggested efferent connections to the arcuate nucleus (44) (see Fig. 1).

The majority of anatomical data suggests that SFO neurons have relatively compact dendritic trees and do not receive extensive neural inputs (22), supporting the suggested principle role of this region in receiving afferent information from peripheral circulation. Limited afferent inputs to the SFO originate from the same areas that receive SFO efferents, including the lateral hypothalamus (70) and the median preoptic nucleus (70), as well as the lateral division of the

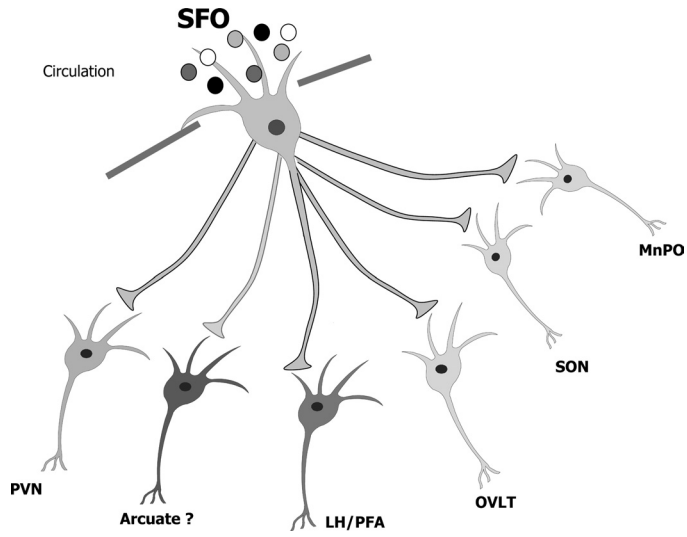


Fig. 1. Schematic representations of subfornical organ (SFO) efferent projections to autonomic nuclei subserving body fluid homeostasis, cardiovascular control, immune regulation, reproductive function and energy homeostasis. PVN, paraventricular nucleus; LH/PFA, lateral hypothalamus/perifornical area; OVLT, organum vasculosum laminae terminalis; SON, supraoptic nucleus; MnPO, median preoptic nucleus.

parabrachial nucleus, nucleus tractus solitarius, midbrain raphé, nucleus reunions of the thalamus, and organum vasculosum of the lamina terminalis (for review, see Ref. 18), suggesting important reciprocal communication between these regions.

*Intrinsic properties of SFO neurons.* The description of SFO as a sensory CVO is effectively a consequence of the ability of SFO neurons to "sense" different physiological signals, responses that are manifested as changes in neuronal excitability. Many studies have described the basic firing patterns and sensitivity of SFO neurons to exogenous hormones and neurotransmitters, as well as important information regarding SFO connectivity and effects of synaptic input on SFO neuronal activity (for review, see Refs. 30 and 76). Voltage-clamp techniques have described voltage-gated sodium, potassium, and calcium currents, as well as hyperpolarization activated ($I_h$), persistent sodium ($I_{NaP}$), swelling activated chloride, and nonselective cationic conductances in SFO neurons (18).

The excitability of subpopulations of neurons within the SFO has been shown to be influenced by osmolarity, calcium, or sodium concentrations in the systemic circulation (for a review, see Ref. 40). Increases in extracellular [$Ca^{2+}$] depolarize SFO neurons as a result of activation of the calcium-sensing receptor, leading to a modulation of nonselective cationic conductance (NSCC), $I_h$, and $I_{NaP}$ (138). Additionally, SFO neurons have been shown to be osmosensitive (3), although the channels underlying this effect have yet to be described. Interestingly, glial cells within the SFO have been shown to express the $Na_X$ channel and respond to changes in extracellular [$Na^+$], suggesting these cells to be true sodium sensors (85).

The presence of peptidergic receptors in SFO has also been used as a logical indicator of the sensory abilities of SFO neurons. In many instances, this surrogate for sensory capability has been supported by later electrophysiological studies confirming neuronal sensitivity. Thus, the description of the presence of ANG II receptors within the SFO (41, 78), was given functional context by many electrophysiological studies showing that SFO neurons are depolarized by increases in ANG II concentrations (28, 31). These findings supported the classical view of the SFO as the primary central site at which circulating ANG II acted to induce drinking (110). More recently, a diverse and growing literature describing actions (receptor localization and electrophysiological effects) of many other circulating factors on SFO neurons has begun to support the concept of a far broader sensory role for neurons in this CVO (see Refs. 40 and 74 for review). SFO neurons have been shown to be sensitive to changes in ACh (28), amylin (93, 97, 99, 115), atrial natriuretic peptides (12), calcitonin (7, 99, 107), endothelin (30, 134, 135), estrogen (136), ghrelin (93), interleukin 1-β (23), oxytocin (52), prokineticin 2 (17, 39), relaxin (123), vasopressin (5, 137), and, most recently, leptin (115) and adiponectin (2) (see Fig. 2). In addition, recent work using whole genome microarray technology has confirmed the presence of receptor and/or protein mRNA for many of the substances listed above (see Figs. 3 and 4), as well as identifying a number of novel transcripts (48), the physiological roles of which have yet to be elucidated. Thus, the perspective emerges of the ability of neurons within the SFO to sense a wide variety of circulating signals, reflecting physiological status and, intriguingly, suggest that this structure may play a role in integrating such signals from multiple physiolog-

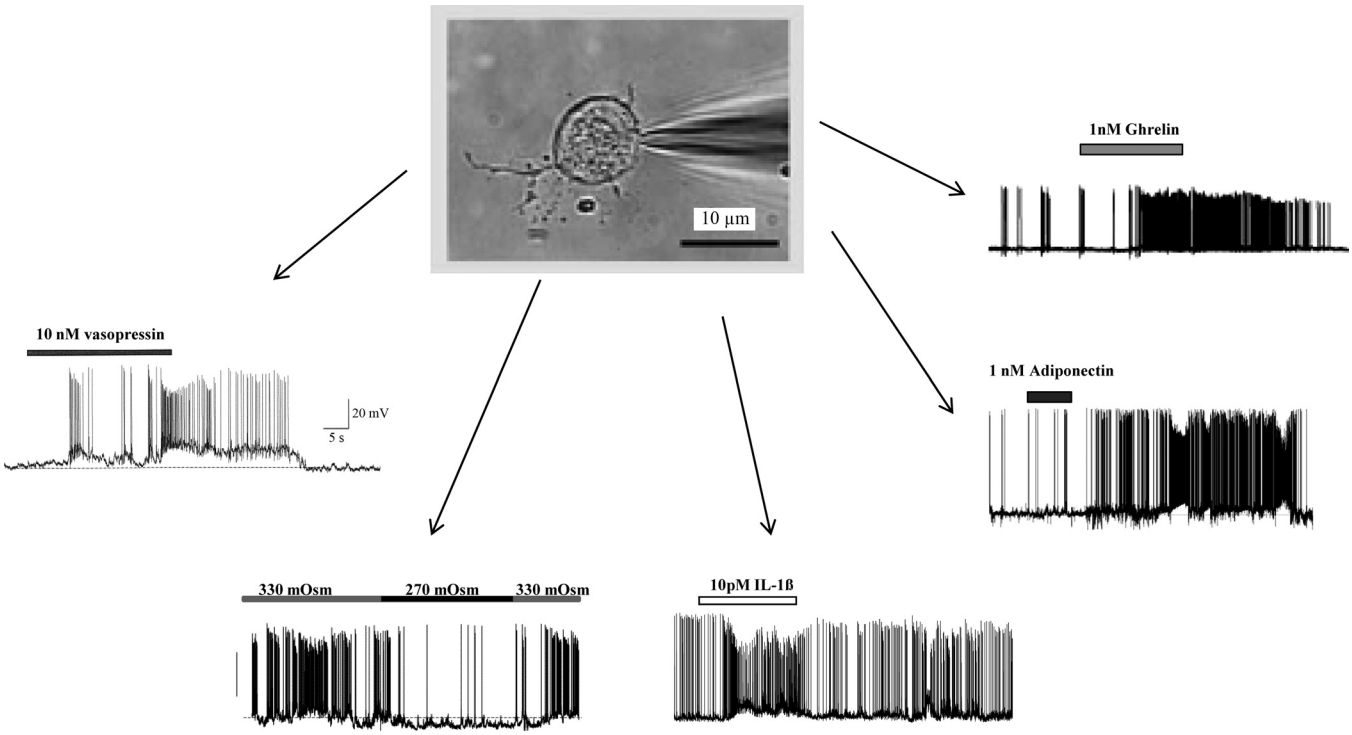


Fig. 2. Signals related to body fluid homeostasis (osmolarity), cardiovascular control, reproductive function (vasopressin), immune regulation (interleukin 1β), feeding, and metabolism (adiponectin and ghrelin) influence the activity of dissociated SFO neurons. Time and duration of peptide application or changes in osmolarity are indicated by the bar at the top of each current clamp recording.

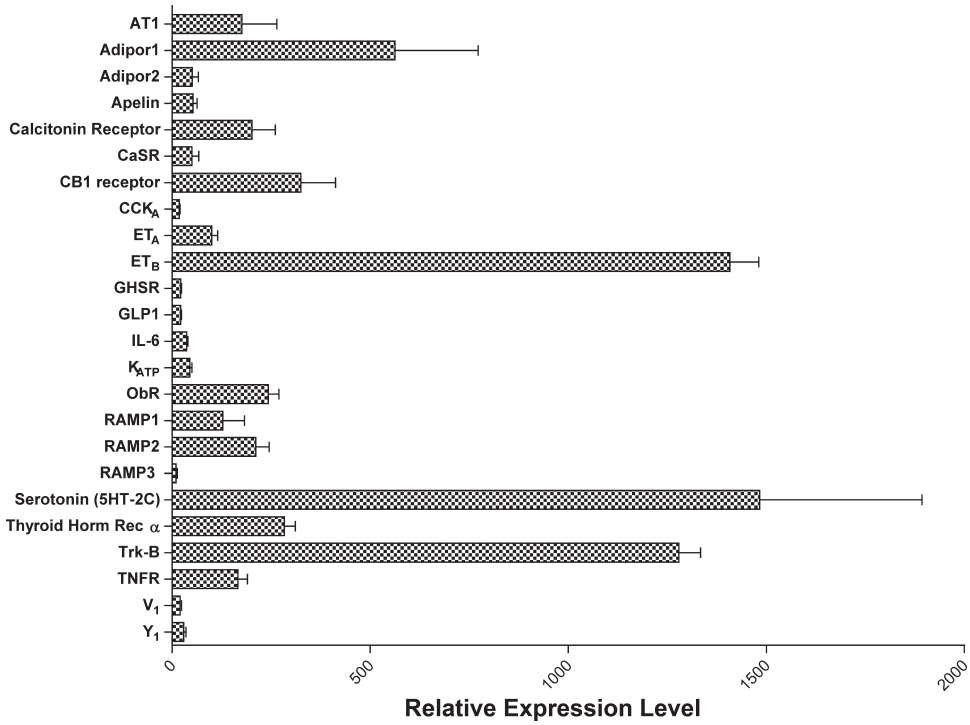


Fig. 3. Summary figure highlights relative expression levels of mRNA for a number of receptors present in SFO (characterized using microarray technology). These data not only confirm the presence of documented receptors shown to be present in SFO but also demonstrate the presence of many novel receptor transcripts not classically associated with the SFO or its primary functions. The presence of novel transcripts, such as the apelin, endocannabinoid (CB1), and thyroid hormone receptor α (Thyroid Horm Rec α) receptors, highlight these as potential targets for future study. AT1, angiotensin II, type 1; Adipor 1, 2, adiponectin receptor 1, 2; CaSR, calcium-sensing receptor; ET, endothelin; GHSR, growth hormone secretagogue receptor; GLP1, glucagon-like peptide 1; ObR, leptin receptor; RAMP, receptor activity-modifying proteins; Trk-B, tropomysin-related kinase B; TNFR, tumor necrosis factor receptor; V1, vasopressin 1; $Y_1$, neuropeptide 1.

ical systems, a number of which we will highlight in the following sections.

*Functional Roles for the SFO*

*Body fluid homeostasis.* Classically, the SFO is known for its well-established roles in the coordination of body fluid balance (30, 74). The initial findings that blood-borne carbachol and ANG II acted at the SFO to elicit drinking behavior in rats (110, 111) and that destruction of the SFO abolished ANG II-induced drinking (112) directed attention to the SFO in the regulation of body fluid balance. The functional importance of SFO in the control of fluid balance was confirmed by later studies showing that destruction of SFO eliminated both water and saline ingestion in rats acutely depleted of sodium (119, 131). In addition, studies showed SFO neurons are activated by water deprivation (20), intravenous injection of hypertonic saline (87, 101), sodium restriction (75), and furosemide-induced sodium depletion (103), many of these effects being abolished by the ANG II antagonist, losartan, or the angiotensin-converting enzyme inhibitor, captopril (75). A role for ANG II receptors within the SFO in controlling sodium appetite has been demonstrated by studies that have shown admin-

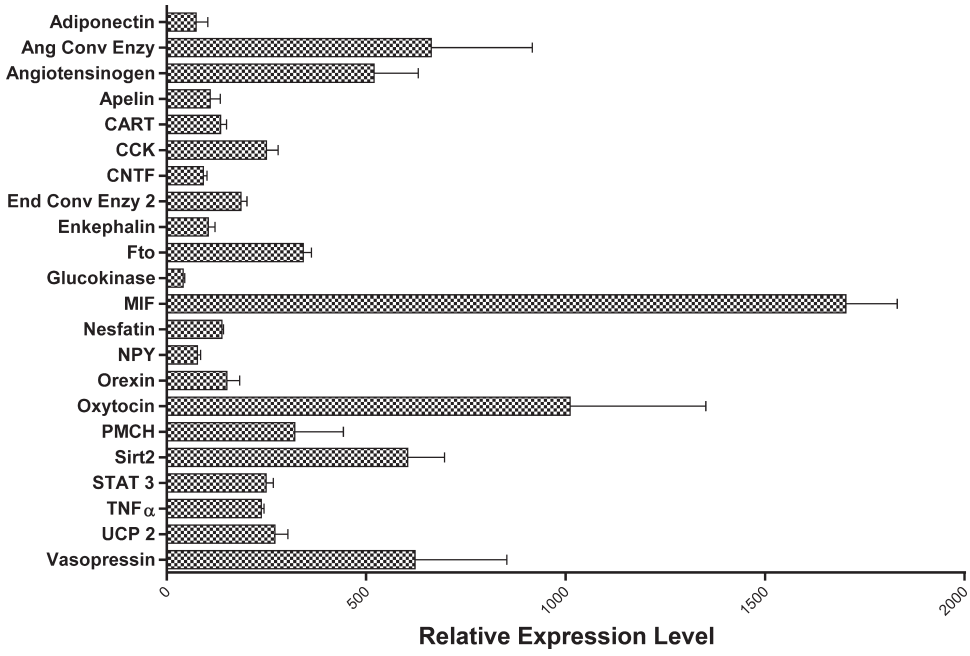


Fig. 4. Relative expression levels of mRNA for peptides present in SFO (characterized using microarray technology). These data not only confirm the presence of documented peptides shown to be present in SFO but also demonstrate the presence of many novel peptide transcripts not classically associated with the SFO or its primary functions. The presence of novel transcripts, such as nesfatin and cocaine and amphetamine regulated transcript (CART), highlight these as potential targets for future study. Ang Conv Enyz, angiontensin-converting enzyme; CART, cocaine- and amphetamine-regulated transcript; CNTF, ciliary neurotrophic factor; End Conv Enzy 2, endothelin-converting enzyme 2; Fto, fat mass and obesity associated; MIF, macrophage migration inhibitory factor; NPY, neuropeptide Y; PMCH, promelanin concentrating hormone; Sirt2, situin 2.

istration of losartan prevents both the marked increase in salt intake induced by furosemide and captopril treatment and the increase in salt and water intake in response to ANG II microinjection into the SFO, which is associated with serotonergic blockade of the lateral parabrachial nucleus (16, 77).

Very high levels of angiotensin-converting enzyme (ACE) have been localized in the SFO (14, 92, 104), and ACE in SFO has been shown to mediate captopril-induced drinking (132), suggesting that local production of ANG II in the SFO may also contribute to the physiological effects of ANG II in this CVO.

Subsequently, the SFO was shown to be sensitive to the sodium and water content of plasma (9, 86, 96), while single-cell recordings have shown that SFO neurons respond to changes in sodium and osmolarity (4, 45). Interestingly, $Na_x$ channels on glial cells in SFO have been shown to sense increases in sodium levels, information that is then transmitted by lactate to influence the activity of GABAergic neurons in the SFO (108). Aquaporin-4, a selective channel specialized for water transport, has been localized in SFO (84), suggesting a mechanism that may contribute, at least in part, to the osmoregulatory role of SFO in volume homeostasis. Functional studies using acute low-intensity electrical stimulation of the SFO have been shown to elicit drinking in satiated rats (114, 117).

Recently, a number of studies have suggested the involvement of additional regulatory molecules (peptidergic and nonpeptidergic) that act in the SFO to regulate volume homeostasis. Leptin, an adipose tissue-derived hormone known primarily for its involvement in energy homeostasis, has been shown to decrease water intake when given systemically (10). Binding sites for stanniocalcin, a circulating hormone that regulates calcium/phosphate homeostasis, have recently been identified in the SFO [and hypothalamic projections sites involved in fluid homeostasis (SON)], further implicating action of this hormone at the SFO in the regulation of fluid homeostasis, electrolyte balance, and cardiovascular regulation (95). Peripheral administration of pilocarpine, a muscarinic receptor agonist, has been shown to facilitate drinking behavior in rats (38, 106). Recent studies revealing *c-fos* immunoreactivity in SFO and patch-clamp recording techniques demonstrating that pilocarpine directly depolarizes SFO neurons by suppressing the release of an inhibitory transmitter (53), suggest that SFO may mediate the dipsogenic effects of exogenous pilocarpine administration. Serotonin receptor mRNA is one of the most highly expressed receptor mRNAs present in the SFO (48), and it has been shown that ANG II reduces the release of serotonin in the SFO, suggesting that serotonin receptors may be involved in the elicitation of drinking behavior by ANG II (127). In addition, it has been demonstrated that serotonergic pathways from the midbrain raphe system to the SFO are activated by hemorrhage in the rat (129), further supporting the role of serotonin in control of fluid balance at the level of the SFO.

Attention has been directed to the involvement of free radicals in SFO by studies showing *rac1*-dependent NADPH oxidase to be a primary source of ANG II-dependent superoxide production in the SFO and that genetic inhibition of this enzyme complex in the SFO attenuated the dipsogenic effects of intracerebroventricular administration of ANG II (142). Specifically, Nox2 has been selectively linked to the dipsogenic effects of intracerebroventricular ANG II administration. (90)

Thus, it is evident that the SFO detects multiple peripheral signals reflecting fluid balance via afferent inputs from multiple sources and relays this information via efferent connections to autonomic control centers, thereby regulating and integrating the functions of many different controllers of overall body fluid homeostasis.

*Cardiovascular regulation.* Microinjection studies showing that direct injection of ANG II into the SFO increased arterial pressure (73), an effect blocked by section of the ventral stalk of the SFO [which is the region in which efferent projections exit the SFO (69)], first focused attention on the potential roles for SFO neurons in cardiovascular regulation. Such roles were later confirmed by reports that stimulation of the SFO by chemical or electrical means causes a biphasic increase in blood pressure, which results in the secretion of vasopressin and oxytocin (33–35, 50, 109) and activation of sympathetic outflow (15, 32). The hypertensive effect of SFO stimulation is prevented by ablation of the hypothalamic PVN (36), suggesting this to be one of the primary efferent output pathways through which SFO neurons elicit such effects. At the cellular level, systemic ANG II acts at the SFO to control the activity of PVN neurons (37, 65) and, interestingly, SFO neurons projecting to PVN have been shown to use ANG II as a neurotransmitter (66). ANG II has been shown to influence the excitability of SFO neurons through the combined inhibition of potassium currents, potentiation of calcium currents, and activation of a nonselective cationic conductance (30, 88, 137). Collectively, these studies suggest that the SFO is a critical relay center through which the CNS is able to monitor circulating ANG II and influence cardiovascular function.

Recent work using site-specific gene ablation techniques to knock down the renin-angiotensin system exclusively in the SFO has intriguingly demonstrated that such manipulation abolished the pressor and bradycardic effects of renin infused in the CNS, providing direct evidence that the local renin-angiotensin system in the SFO plays a critical role in blood pressure regulation (113). In addition, the use of viral vectors to cause the overexpression of ACE2 specifically in SFO reduced the pressor (and dipsogenic) response elicited by intracerebroventricular ANG II and was associated with down-regulation of ANG II type 1 receptor expression (29). These observations suggest a new target for the treatment of hypertension and other cardiovascular diseases.

Other regulatory peptides known for effects on the cardiovascular system that have been shown to influence blood pressure as a result of actions in the SFO include vasopressin (116, 137) and atrial natriuretic peptide (105). In addition, the reproductive hormone, relaxin (82), the orexigenic and arousal neuropeptide, orexin (118), and the adipose tissue-derived hormone, leptin (P. Smith and A. Ferguson, unpublished observation) have also been shown to influence blood pressure when microinjected into the SFO. Galanin has been shown to inhibit the electrical activation of ANG II-sensitive neurons in the SFO (54), and while intracerebroventricular injection of galanin in conscious rats results in small pressor response, it has been shown to inhibit ANG II-induced pressor responses (49), suggesting a role in mediating cardiovascular control through actions at the SFO. It has also been suggested that cardiovascular responses seen in response to intravenous ad-

ministration of subseptic levels of LPS, a bacterial endotoxin (see *Immune regulation*), may be responsible for early IL-1β gene expression in the SFO (141).

Recent attention has focused on the role of oxidative stress on the development of hypertension, and superoxide has been identified as a particularly important free radical in cardiovascular biology. Recent work has suggested a role for superoxide in SFO in mediating ANG II-induced cardiovascular effects (143). Using adenovirus-mediated delivery of siRNA to the SFO, Peterson et al. (90) have shown that NADPH oxidase homologues (Nox2 and Nox4) contribute to the cardiovascular responses elicited by intracerebroventricular administration of ANG II (90). Myocardial infarction (MI) has also been shown to increase superoxide production in the SFO, while prevention of such changes in the SFO following MI led to significantly improved myocardial function and diminished levels of cardiomyocyte apoptosis (72). Finally, scavenging superoxide in mouse forebrain is associated with improved cardiac function and survival following myocardial infarction (72). Together, these studies suggest that oxidative stress in the SFO plays a critical role in the deterioration of cardiac function following myocardial infarction and suggests a CNS target for antioxidant therapy directed toward the treatment of myocardial infarction-induced heart failure.

The evidence presented above suggests that SFO involvement in cardiovascular regulation is multifaceted and involves a number of signaling molecules, many of which are not "classical" cardiovascular mediators. This then further suggests an integrative role for the SFO in detecting and assimilating information from a variety of sources, relaying this information to the appropriate autonomic control centers to facilitate an appropriate coordinated autonomic response.

*Immune regulation.* Systemic signaling of infection can occur directly through bacterial endotoxins, such as LPS or through pyrogenic cytokines, such as the interleukins (IL-1β and IL-6), which, in turn, act at the brain to cause an integrated immune response, including changes in body temperature, hormone release, sleep patterns, and food intake. The CVOs have been suggested to provide both an access point to the brain for endotoxins and cytokines and, through their efferent connections to hypothalamic and medullary autonomic centers, potentially integrate the multiple components of this coordinated response.

The identification of interleukin-1β and CD14 (the classic marker for endotoxin binding) receptors in the SFO (19, 27, 60), as well as receptor mRNA for other known mediators of the immune response, including ciliary neurotrophic factor (48) and tumor necrosis factor-α (48, 83), suggest that the SFO may play an important role in immune regulation.

Functional relevance to expression of these receptors in SFO is derived from studies demonstrating that peripheral administration of interleukin-1β induces *c-fos* expression in SFO neurons (26) , which is further supported by electrophysiological studies showing that IL-1β depolarize SFO neurons as a result of modulation of a nonselective cationic conductance (23). In addition, in vivo studies have revealed that SFO lesions inhibit LPS fever generation (124), a conclusion further supported by the demonstration that microinjection of the interleukin-1 receptor antagonist into SFO also attenuates LPS-induced fever (13).

While systemic administration of the high doses of LPS has been shown to cause a robust and widespread induction of *c-fos* mRNA within the CNS and induce global expression of proinflammatory cytokines in the brain, subseptic doses of LPS caused the selective triggering of *c-fos* expression within discrete brain regions, including the SFO (59), and caused the induction of IL-1β and TNF-α mRNA expression only in the choroid plexus, the circumventricular organs, including the SFO and meninges. These results indicate that the actions of proinflammatory cytokines during subseptic infection may occur at the SFO, which, in turn, communicates this peripheral immune status to the autonomic control centers in the brain (94). It has also been suggested that differential cardiovascular responses observed in response to subseptic levels of endotoxins may underlie these differences (141).

Constitutive CD14 labeling has been demonstrated in the SFO, and LPS treatment has been shown to cause a robust increase in CD14 expression and a rapid induction of IL-1β, IL-6, and TNF-α within SFO (60). TNF acts via two cell-surface receptors, the p55 and p75 TNF receptors. Constitutive expression of p55 mRNA has been demonstrated in the SFO, and functional activation of this receptor by circulating TNF-α has been shown to induce *c-fos* expression in the SFO (83).

Toll-like receptors have been suggested to play a key role in the innate immune response and, not only has Toll-like receptor 4 mRNA been localized in the SFO, but a decreased receptor expression is also seen in response to systemic LPS or IL-1β challenge (60). In contrast to the strong upregulation of the gene-encoding mCD14 during endotoxemia, neither LPS nor IL-1β caused a convincing increase in the Toll-like receptor 4 mRNA. The constitutive expression of both mCD14 and Toll-like receptor 4 may explain the innate immune response in the brain, which originates from the structures devoid of the BBB, such as the SFO, in the presence of circulating LPS (60).

IL-6, an endogenous mediator of LPS-induced fever, has been shown to directly activate SFO neurons as revealed by the demonstration of a nuclear translocation (and thus activation) of the transcription factor, signal transducer, and activator of transcription 3 (STAT3) within SFO (46, 58). In addition, suppressors of cytokine signaling (SOCS), cytokine-inducible proteins, are rapidly induced by IL-6, and peripheral LPS administration has been shown to cause a profound transcriptional activation of SOCS-3 mRNA in SFO in a time-dependent manner (63).

Thus, although the data suggesting sensory roles for the SFO in the regulation of immune function are not as extensive as that for fluid balance, there is strong evidence that support the proposed role of the SFO as a sensor of humoral signals (endotoxins or cytokines) produced by the activated immune system, which act centrally to initiate the integrated immune response.

*Reproduction.* A role for the SFO in the control of reproductive function was first suggested by lesions studies showing that removal of SFO disrupted the estrous cycle and forced rats into a prolonged state of diestrus (67). In addition, the proestrous follicle-stimulating hormone surge was absent, while the luteinizing hormone secretion remained unchanged in SFO-lesioned rats, suggesting that the SFO may play a role in the control of the cyclic release of these two gonadotropins (67). The SFO has also been found to contain significant levels of gonadotropin-releasing hormone (57), al-

though the specific impact of this expression is not known. However, studies have demonstrated excitatory inputs from SFO to putative GnRH neurons (24) and that activation of SFO neurons results in increased circulating concentrations of luteinizing hormone (25).

Although it is known that circulating estrogens influence the electrical activity of the hypothalamic magnocellular neurons, which synthesize vasopressin or oxytocin and regulate body fluid homeostasis and reproduction, none of these magnocellular neurons express the estrogen receptor. Estrogen receptors have been localized within the SFO (102), and it has been demonstrated that SFO neurons expressing the estrogen receptor project to the SON, thus providing a route through which circulating estrogen could exert its effect on the excitability of SON neurons (133). It has also been suggested that circulating estrogens act at receptors in SFO to modulate the role of ANG II in the regulation of fluid and electrolyte balance (102, 126, 128). The SFO has also been shown to have high densities of binding sites for relaxin, a peptide produced primarily by the ovary of pregnant animals, as well as in the brain. Relaxin has been shown to influence the activity of SFO neurons (123), suggesting that this CVO may be involved in controlling the duration of gestation (121) and the milk ejection reflex (120). Relaxin has also been shown to cause hypertension as a result of actions at the SFO (121). Exogenous administration of relaxin has been shown to have a profound dipsogenic response (51, 123, 130). Blockade of the ANG II receptor negates several central actions of relaxin, while expression of $AT_1$ receptors in the SFO increases in parallel with the increase in circulating relaxin seen in the second half of pregnancy (51), suggesting that relaxin may be important for the normal physiology of pregnancy.

*Feeding and metabolism.* Until recently, the area postrema, located in the medulla, was thought to be the predominant CVO involved in the regulation of food intake. Interestingly, recent work reporting receptor mRNA for a number of feeding-related peptides in the SFO (48), and single-cell recordings, showing effects of functional activation of these receptors on the excitability of SFO neurons (see Fig. 2) has begun to focus attention on potential roles for this forebrain CVO in the sensation and integration of satiety signals. Calcitonin (107) and the satiation signal, amylin (97, 98), have been shown to influence the activity of SFO neurons. Our own recent work has shown neurons within the SFO to be excited by amylin or the meal initiation peptide, ghrelin, although none of these cells were excited by both peptides (93), suggesting that different subpopulations of neurons in the SFO differentially mediate the appetite-suppressing and appetite-stimulatory effects of these peptides.

Systemic ghrelin administration has been shown to induce the neural expression of c-Fos protein in the SFO, suggesting that ghrelin, released into the circulation, may stimulate SFO neurons (125). Peripherally administered amylin has been shown to induce an anorexigenic effect as a consequence of a reduction in meal size, as has peripheral administration of the amylin-related peptide, salmon calcitonin (21).

We have also demonstrated that the SFO possesses receptors for the adiposity signals leptin (115) and adiponectin (2) and that functional activation of these receptors influences the excitability of SFO neurons (2, 115). In addition, leptin and amylin, which both decrease food intake, have been shown to depolarize the same SFO neurons (115).

The melanocortin and neuropeptide Y systems have been shown to play important roles in feeding and metabolism. Both melanocortin 4 receptor (48, 56) and Y1 receptor mRNA (48, 55) have been observed in the SFO, suggesting a role for the SFO in mediating the effects on feeding elicited by α-melanocyte-stimulating hormone and neuropeptide Y, the endogenous ligands for melanocotin 4 receptor and Y1 receptor, respectively.

SIRT1, a NAD-dependent deacetylase, has been suggested to be an important link between energy metabolism and aging, and mRNA for this enzyme has been localized in the SFO, with intriguing age and sex-related differential expression reported (61). Resveratrol, an activator of SIRT1 (11), inhibits the electrical activity of SFO neurons perhaps due to blockade of L-type voltage-gated calcium channels (64). Interestingly, resveratrol has been shown to improve the survival of mice fed a high-calorie diet (8), and it has been suggested to protect against metabolic disease through the activation of SIRT1 (62). SIRT1 activation by resveratrol has also been shown to down-regulate $AT_1$ receptor expression (81). Thus, it appears that the inhibition of the renin-angiotensin system may contribute, at least in part, to the resveratrol-induced longevity and anti-atherogenic effect of resveratrol, and, although not yet investigated, an effect that may be mediated at the SFO.

Finally, our own recent behavioral studies have shown that short-duration, low-intensity electrical stimulation in SFO induces feeding in satiated rats (117), providing functional evidence for the involvement of SFO neurons in the control of energy homeostasis.

### *Subfornical Organ as a Controller of Integrated Autonomic Function*

As illustrated in the previous sections, it is apparent that a single peptide (i.e., angiotensin) can have a variety of physiological actions, including behavioral (drinking), neuroendocrine (control of ACTH, oxytocin, vasopressin secretion), and autonomic (sympathetic activation) effects, as a direct consequence of actions in the CNS and that many of these action are mediated, at least in part, by actions at the SFO.

As highlighted above, the SFO is sensitive to a wide variety of circulating signals, and it is now becoming clear that the sensory abilities of SFO neurons are far more sophisticated than was initially imagined. In addition to its unique position at the blood-brain interface, the SFO combines broad-ranging sensory abilities with the capability to exert control over interrelated, yet diverse physiological systems. Nearly all studies examining the sensitivity of SFO neurons to these circulating signals report that between 25% and 60% of neurons are influenced, suggesting that single neurons must have multiple sensory abilities. This concept, at the minimal level of two signals, has been confirmed in SFO neurons, which are ANG II and osmosensitive (3), ANG II and atrial natriuretic peptide sensitive (47), ANG II and calcitonin responsive (107), ANG II and estrogen responsive (128), and leptin and amylin sensitive (115). Whether single SFO neurons are, therefore, ANG II, atrial natriuretic peptide, calcitonin, estradiol, leptin osmosensitive represents an intriguing and important question, as well as a somewhat daunting experimental challenge. However, in the

advent of single-cell RT-PCR and single-cell gene array analysis, there is the potential in the immediate future to provide answers to this important question.

There is to date no information regarding the ability of single CVO neurons to sense multiple signals, which would traditionally be viewed as related to different physiological systems. For example, are leptin and amylin (energy homeostasis)-sensitive SFO neurons also sensitive to ANG II (body fluid homeostasis)? Again, the fact that over 60% of SFO neurons are ANG II sensitive and leptin influences the excitability of 60% of SFO neurons (115) implies that there must be a population of SFO neurons that would be responsive to both ANG II and leptin. Behavioral studies demonstrating that, in addition to the decrease in food intake observed in response to peripheral administration of leptin, water intake was also reduced (10) and that ACE inhibitors decrease body weight in mice fed a high-fat diet (139) also supports this hypothesis. The pregnancy hormone relaxin may also play a role in body fluid homeostasis as exogenous administration of relaxin into the brain causes a profound drinking response (51, 123, 130), and expression of $AT_1$ receptors in the SFO increases in parallel with the increase in circulating relaxin seen in the second half of pregnancy (51).

*Perspectives and Significance*

In light of the above evidence, the capacity of SFO neurons to sense multiple signals and thus control, in an integrated manner, broader-based physiological outputs (i.e., energy homeostasis, cardiovascular regulation, reproduction, and body fluid homeostasis) is emerging. However, research directed toward understanding central control of fluid balance, cardiovascular regulation, immune regulation, reproductive function, and energy homeostasis remains clearly separated into distinct fields. Although experimentally, divisions along the lines of distinct autonomic function make sense, this separation, physiologically, does not. Humans very seldom eat without drinking. Impaired energy homeostasis (i.e., obesity) is often associated with cardiovascular pertubuations (hypertension) and reproductive dysfunction. Lack of available nutrients or the converse, profound obesity, has clear inhibitory effects on reproductive function, and systemic infections not only activate the neuroimmune axis but also profoundly influence fluid and food intake.

Thus, it seems that SFO neurons, which are uniquely positioned at the blood-brain interface, have the capacity to coordinate physiological responses elicited by the various autonomic control signals, thereby establishing and maintaining an autonomic state for the entire organism, rather than for isolated individual parameters. It would seem, then, that to understand such potentially integrative roles of the SFO, we will need to take a far more integrative approach to the design of experiments, which can assess the coordinated contributions of the SFO.

**GRANTS**

This work was supported by operating grants to A. V. Ferguson from the Canadian Institutes for Health Research (CIHR) and the Heart and Stroke Foundation of Ontario, and a Team Grant from CIHR to A. V. Ferguson. P. M. Smith was supported by a studentship from CIHR.

**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the authors.

**REFERENCES**

1. **Abbott NJ, Ronnback L, Hansson E.** Astrocyte-endothelial interactions at the blood-brain barrier. *Nat Rev Neurosci* 7: 41–53, 2006.
2. **Alim I, Fry WM, Ferguson AV.** Actions of adiponectin on the excitability of subfornical organ neurons are altered by food deprivation. *Brain Res* 12: 72–82, 2010.
3. **Anderson JW, Smith PM, Ferguson AV.** Subfornical organ neurons projecting to paraventricular nucleus: whole-cell properties. *Brain Res* 921: 78–85, 2001.
4. **Anderson JW, Washburn DL, Ferguson AV.** Intrinsic osmosensitivity of subfornical organ neurons. *Neuroscience* 100: 539–547, 2000.
5. **Anthes N, Schmid HA, Hashimoto H, Riediger T, Simon E.** Heterogeneous actions of vasopressin on ANG II-sensitive neurons in the subfornical organ of rats. *Am J Physiol Regul Integr Comp Physiol* 273: R2105–R2111, 1997.
6. **Banks WA.** Blood-brain barrier transport of cytokines: a mechanism for neuropathology. *Curr Pharm Des* 11: 973–984, 2005.
7. **Barth SW, Riediger T, Lutz TA, Rechkemmer G.** Peripheral amylin activates circumventricular organs expressing calcitonin receptor a/b subtypes and receptor-activity modifying proteins in the rat. *Brain Res* 997: 97–102, 2004.
8. **Baur JA, Pearson KJ, Price NL, Jamieson HA, Lerin C, Kalra A, Prabhu VV, Allard JS, Lopez-Lluch G, Lewis K, Pistell PJ, Poosala S, Becker KG, Boss O, Gwinn D, Wang M, Ramaswamy S, Fishbein KW, Spencer RG, Lakatta EG, Le CD, Shaw RJ, Navas P, Puigserver P, Ingram DK, de CR, Sinclair DA.** Resveratrol improves health and survival of mice on a high-calorie diet. *Nature* 444: 337–342, 2006.
9. **Bisley JW, Rees SM, McKinley MJ, Hards DK, Oldfield BJ.** Identification of osmoresponsive neurons in the forebrain of the rat: a fos study at the ultrastructural level. *Brain Res* 720: 25–34, 1996.
10. **Bojanowska E, Nowak A.** Interactions between leptin and exendin-4, a glucagon-like peptide-1 agonist, in the regulation of food intake in the rat. *J Physiol Pharmacol* 58: 349–360, 2007.
11. **Borra MT, Smith BC, Denu JM.** Mechanism of human SIRT1 activation by resveratrol. *J Biol Chem* 280: 17187–17195, 2005.
12. **Buranarugsa P, Hubbard JI.** Excitatory effects of atrial natriuretic peptide on rat subfornical organ neurons in vitro. *Brain Res Bull* 20: 627–631, 1988.
13. **Cartmell T, Luheshi GN, Rothwell NJ.** Brain sites of action of endogenous interleukin-1 in the febrile response to localized inflammation in the rat. *J Physiol* 518: 585–594, 1999.
14. **Chai SY, Allen AM, Adam WR, Mendelsohn FA.** Local actions of angiotensin II: quantitative in vitro autoradiographic localization of angiotensin II receptor binding and angiotensin converting enzyme in target tissues. *J Cardiovasc Pharmacol* 8 *Suppl* 10: S35–S39, 1986.
15. **Ciriello J, Gutman MB.** Functional identification of central pressor pathways originating in the subfornical organ. *Can J Physiol Pharmacol* 69: 1035–1045, 1991.
16. **Colombari DS, Menani JV, Johnson AK.** Forebrain angiotensin type 1 receptors and parabrachial serotonin in the control of NaCl and water intake. *Am J Physiol Regul Integr Comp Physiol* 271: R1470–R1476, 1996.
17. **Cottrell GT, Zhou QY, Ferguson AV.** Prokineticin 2 modulates the excitability of subfornical organ neurons. *J Neurosci* 24: 2375–2379, 2004.
18. **Cottrell GT, Ferguson AV.** Sensory circumventricular organs: central roles in integrated autonomic regulation. *Regul Pept* 117: 11–23, 2004.
19. **Cunningham ET Jr, Wada E, Carter DB, Tracey DE, Battey JF, and De Souza EB.** In situ histochemical localization of type I interleukin-1 receptor messenger RNA in the central nervous system, pituitary, and adrenal gland of the mouse. *J Neurosci* 12: 1101–1114, 1992.
20. **De Luca LA Jr, Xu Z, Schoorlemmer GH, Thunhorst RL, Beltz TG, Menani JV, Johnson AK.** Water deprivation-induced sodium appetite: humoral and cardiovascular mediators and immediate early genes. *Am J Physiol Regul Integr Comp Physiol* 282: R552–R559, 2002.
21. **Del PE, Schade B, Riediger T, Lutz TA, Scharrer E.** Effects of amylin and salmon calcitonin on feeding and drinking behavior in pygmy goats. *Physiol Behav* 75: 593–599, 2002.
22. **Dellman HD, Simpson JB.** The subfornical organ. *Int Rev Cytol* 58: 333–421, 1979.
23. **Desson SE, Ferguson AV.** Interleukin 1β modulates rat subfornical organ neurons as a result of activation of a non-selective cationic conductance. *J Physiol* 550: 113–122, 2003.

24. **Donevan SD, Ferguson AV.** Subfornical organ connections with septal neurons projecting to the median eminence. *Neuroendocrinology* 48: 67–71, 1988.
25. **Donevan SD, Van Vugt DA, Ferguson AV.** Subfornical organ activation stimulates luteinizing hormone secretion in the rat. *Brain Res* 488: 398–402, 1989.
26. **Elmquist JK, Scammell TE, Jacobson CD, Saper CB.** Distribution of Fos-like immunoreactivity in the rat brain following intravenous lipopolysaccharide administration. *J Comp Neurol* 371: 85–103, 1996.
27. **Ericsson A, Liu C, Hart RP, Sawchenko PE.** Type 1 interleukin-1 receptor in the rat brain: distribution, regulation, and relationship to sites of IL-1-induced cellular activation. *J Comp Neurol* 361: 681–698, 1995.
28. **Felix D.** Peptide and acetylcholine action on neurones of the cat subfornical organ. *Naunyn Schmiedebergs Arch Pharmacol* 292: 15–20, 1976.
29. **Feng Y, Yue X, Xia H, Bindom SM, Hickman PJ, Filipeanu CM, Wu G, Lazartigues E.** Angiotensin-converting enzyme 2 overexpression in the subfornical organ prevents the angiotensin II-mediated pressor and drinking responses and is associated with angiotensin II type 1 receptor downregulation. *Circ Res* 102: 729–736, 2008.
30. **Ferguson AV, Bains JS.** Electrophysiology of the circumventricular organs. *Front Neuroendocrinol* 17: 440–475, 1996.
31. **Ferguson AV, Bains JS.** Actions of angiotensin in the subfornical organ and area postrema: implications for long-term control of autonomic output. *Clin Exp Pharmacol Physiol* 24: 96–101, 1997.
32. **Ferguson AV, Day TA, Renaud LP.** Subfornical organ stimulation excites paraventricular neurons projecting to the dorsal medulla. *Am J Physiol Regul Integr Comp Physiol* 247: R1088–R1092, 1984.
33. **Ferguson AV, Kasting NW.** Electrical stimulation in the subfornical organ increases plasma vasopressin concentrations in the conscious rat. *Am J Physiol Regul Integr Comp Physiol* 251: R425–R428, 1986.
34. **Ferguson AV, Kasting NW.** Activation of subfornical organ efferents stimulates oxytocin secretion in the rat. *Regul Pept* 18: 93–100, 1987.
35. **Ferguson AV, Kasting NW.** Angiotensin acts at the subfornical organ to increase plasma oxytocin concentrations in the rat. *Regul Pept* 23: 343–352, 1988.
36. **Ferguson AV, Renaud LP.** Hypothalamic paraventricular nucleus lesions decrease pressor responses to subfornical organ stimulation. *Brain Res* 305: 361–364, 1984.
37. **Ferguson AV, Renaud LP.** Systemic angiotensin acts at subfornical organ to facilitate activity of neurohypophysial neurons. *Am J Physiol Regul Integr Comp Physiol* 251: R712–R717, 1986.
38. **Fregly MJ.** Attenuation of pilocarpine-induced drinking by chronic treatment with estrogens. *Proc Soc Exp Biol Med* 164: 178–183, 1980.
39. **Fry M, Cottrell GT, Ferguson AV.** Prokineticin 2 influences subfornical organ neurons through regulation of MAP kinase and the modulation of sodium channels. *Am J Physiol Regul Integr Comp Physiol* 295: R848–R856, 2008.
40. **Fry M, Hoyda TD, Ferguson AV.** Making sense of it: roles of the sensory circumventricular organs in feeding and regulation of energy homeostasis. *Exp Biol Med* 232: 14–26, 2007.
41. **Gehlert DR, Gackenheimer SL, Reel JK, Lin HS, Steinberg MI.** Non-peptide angiotensin II receptor antagonists discriminate subtypes of $^{125}$I-angiotensin II binding sites in the rat brain. *Eur J Pharmacol* 187: 123–126, 1990.
42. **Gross PM.** Morphology and physiology of capillary systems in subregions of the subfornical organ and area postrema. *Can J Physiol Pharmacol* 69: 1010–1025, 1991.
43. **Gross PM.** Circumventricular organ capillaries. *Prog Brain Res* 91: 219–233, 1992.
44. **Gruber K, McRae-Degueurce A, Wilkin LD, Mitchell LD, Johnson AK.** Forebrain and brainstem afferents to the arcuate nucleus in the rat: potential pathways for the modulation of hypophyseal secretions. *Neurosci Lett* 75: 1–5, 1987.
45. **Gutman MB, Ciriello J, Mogenson GJ.** Effects of plasma angiotensin II and hypernatremia on subfornical organ neurons. *Am J Physiol Regul Integr Comp Physiol* 254: R746–R754, 1988.
46. **Harre EM, Roth J, Pehl U, Kueth M, Gerstberger R, Hubschle T.** Selected contribution: role of IL-6 in LPS-induced nuclear STAT3 translocation in sensory circumventricular organs during fever in rats. *J Appl Physiol* 92: 2657–2666, 2002.
47. **Hattori Y, Kasai M, Uesugi S, Kawata M, Yamashita H.** Atrial natriuretic polypeptide depresses angiotensin II-induced excitation of neurons in the rat subfornical organ in vitro. *Brain Res* 443: 355–359, 1988.
48. **Hindmarch C, Fry M, Yao ST, Smith PM, Murphy D, Ferguson AV.** Microarray analysis of the transcriptome of the subfornical organ in the rat: regulation by fluid and food deprivation. *Am J Physiol Regul Integr Comp Physiol* 295: R1914–R1920, 2008.
49. **Hirase M, Ono K, Yamashita H, Inenaga K.** Central injection of galanin inhibits angiotensin II-induced responses in rats. *Neuroreport* 19: 323–326, 2008.
50. **Holmes MC, Catt KJ, Aguilera G.** Involvement of vasopressin in the down-regulation of pituitary corticotropin-releasing factor receptors after adrenalectomy. *Endocrinology* 121: 2093–2098, 1987.
51. **Hornsby DJ, Wilson BC, Summerlee AJ.** Relaxin and drinking in pregnant rats. *Prog Brain Res* 133: 229–240, 2001.
52. **Hosono T, Schmid HA, Kanosue K, Simon E.** Neuronal actions of oxytocin on the subfornical organ of male rats. *Am J Physiol Endocrinol Metab* 276: E1004–E1008, 1999.
53. **Inenaga K, Wakasugi-Sato N, Ono K, Hirase M, Honda E.** Intraperitoneal injection of pilocarpine activates neurons in the circumventricular organs and hypothalamus in rats. *Brain Res* 1200: 51–57, 2008.
54. **Kai A, Ono K, Kawano H, Honda E, Nakanishi O, Inenaga K.** Galanin inhibits neural activity in the subfornical organ in rat slice preparation. *Neuroscience* 143: 769–777, 2006.
55. **Kishi T, Aschkenasi CJ, Choi BJ, Lopez ME, Lee CE, Liu H, Hollenberg AN, Friedman JM, Elmquist JK.** Neuropeptide Y Y1 receptor mRNA in rodent brain: distribution and colocalization with melanocortin-4 receptor. *J Comp Neurol* 482: 217–243, 2005.
56. **Kishi T, Aschkenasi CJ, Lee CE, Mountjoy KG, Saper CB, Elmquist JK.** Expression of melanocortin 4 receptor mRNA in the central nervous system of the rat. *J Comp Neurol* 457: 213–235, 2003.
57. **Kizer JS, Palkovits M, Brownstein MJ.** Releasing factors in the circumventricular organs of the rat brain. *Endocrinology* 98: 311–317, 1976.
58. **Knorr C, Hubschle T, Murgott J, Muhlradt P, Gerstberger R, Roth J.** Macrophage-activating lipopeptide-2 (MALP-2) induces a localized inflammatory response in rats resulting in activation of brain sites implicated in fever. *Brain Res* 1205: 36–46, 2008.
59. **Lacroix S, Rivest S.** Functional circuitry in the brain of immune-challenged rats: partial involvement of prostaglandins. *J Comp Neurol* 387: 307–324, 1997.
60. **Laflamme N, Rivest S.** Toll-like receptor 4: the missing link of the cerebral innate immune response triggered by circulating gram-negative bacterial cell wall components. *FASEB J* 15: 155–163, 2001.
61. **Lafontaine-Lacasse M, Richard D, Picard F.** Effects of age and gender on Sirt 1 mRNA expressions in the hypothalamus of the mouse. *Neurosci Lett* In press.
62. **Lagouge M, Argmann C, Gerhart-Hines Z, Meziane H, Lerin C, Daussin F, Messadeq N, Milne J, Lambert P, Elliott P, Geny B, Laakso M, Puigserver P, Auwerx J.** Resveratrol improves mitochondrial function and protects against metabolic disease by activating SIRT1 and PGC-1$\alpha$. *Cell* 127: 1109–1122, 2006.
63. **Lebel E, Vallieres L, Rivest S.** Selective involvement of interleukin-6 in the transcriptional activation of the suppressor of cytokine signaling-3 in the brain during systemic immune challenges. *Endocrinology* 141: 3749–3763, 2000.
64. **Li M, Wang QS, Chen Y, Wang ZM, Liu Z, Guo SM.** Resveratrol inhibits the electrical activity of subfornical organ neurons in rat. *Sheng Li Xue Bao* 57: 523–528, 2005.
65. **Li Z, Ferguson AV.** Angiotensin II responsiveness of rat paraventricular and subfornical organ neurons in vitro. *Neuroscience* 55: 197–207, 1993.
66. **Li Z, Ferguson AV.** Subfornical organ efferents to the paraventricular nucleus utilize angiotensin as a neurotransmitter. *Am J Physiol Regul Integr Comp Physiol* 265: R302–R309, 1993.
67. **Limonta P, Maggi R, Giudici D, Martini L, Piva F.** Role of the subfornical organ (SFO) in the control of gonadotropin secretion. *Brain Res* 229: 75–84, 1981.
68. **Lind RW.** Bi-directional, chemically specified neural connections between the subfornical organ and the midbrain raphe system. *Brain Res* 384: 250–261, 1986.
69. **Lind RW, Ohman LE, Lansing MB, Johnson AK.** Transection of subfornical organ neural connections diminishes the pressor response to intravenously infused angiotensin II. *Brain Res* 275: 361–364, 1983.
70. **Lind RW, Swanson LW, Ganten D.** Angiotensin II immunoreactivity in the neural afferents and efferents of the subfornical organ of the rat. *Brain Res* 321: 209–215, 1984.

71. **Lind RW, Van Hoesen GW, Johnson AK.** An HRP study of the connections of the subfornical organ of the rat. *J Comp Neurol* 210: 265–277, 1982.
72. **Lindley TE, Infanger DW, Rishniw M, Zhou Y, Doobay MF, Sharma RV, Davisson RL.** Scavenging superoxide selectively in mouse forebrain is associated with improved cardiac function and survival following myocardial infarction. *Am J Physiol Regul Integr Comp Physiol* 296: R1–R8, 2009.
73. **Mangiapane ML, Simpson JB.** Subfornical organ lesions reduce the pressor effect of systemic angiotensin II. *Neuroendocrinology* 31: 380–384, 1980.
74. **McKinley MJ, Allen AM, Burns P, Colvill LM, Oldfield BJ.** Interaction of circulating hormones with the brain: the roles of the subfornical organ and the organum vasculosum of the lamina terminalis. *Clin Exp Pharmacol Physiol Suppl* 25: S61–S67, 1998.
75. **McKinley MJ, Colvill LM, Giles ME, Oldfield BJ.** Distribution of Fos-immunoreactivity in rat brain following a dipsogenic dose of captopril and effects of angiotensin receptor blockade. *Brain Res* 747: 43–51, 1997.
76. **McKinley MJ, McAllen RM, Davern P, Giles ME, Penschow J, Sunn N, Uschakov A, Oldfield BJ.** The sensory circumventricular organs of the mammalian brain. *Adv Anat Embryol Cell Biol* 172: 1–122, 2003.
77. **Menani JV, Colombari DS, Beltz TG, Thunhorst RL, Johnson AK.** Salt appetite: interaction of forebrain angiotensinergic and hindbrain serotonergic mechanisms. *Brain Res* 801: 29–35, 1998.
78. **Mendelsohn FA, Quirion R, Saavedra JM, Aguilera G, Catt KJ.** Autoradiographic localization of angiotensin II receptors in rat brain. *Proc Natl Acad Sci USA* 81: 1575–1579, 1984.
79. **Miselis RR.** The subfornical organ's neural connections and their role in water balance. *Peptides* 3: 501–502, 1982.
80. **Miselis RR, Shapiro RE, Hand PJ.** Subfornical organ efferents to neural systems for control of body water. *Science* 205: 1022–1025, 1979.
81. **Miyazaki R, Ichiki T, Hashimoto T, Inanaga K, Imayama I, Sadoshima J, Sunagawa K.** SIRT1, a longevity gene, downregulates angiotensin II type 1 receptor expression in vascular smooth muscle cells. *Arterioscler Thromb Vasc Biol* 28: 1263–1269, 2008.
82. **Mumford AD, Parry LJ, Summerlee AJ.** Lesion of the subfornical organ affects the haemotensive response to centrally administered relaxin in anaesthetized rats. *J Endocrinol* 122: 747–755, 1989.
83. **Nadeau S, Rivest S.** Effects of circulating tumor necrosis factor on the neuronal activity and expression of the genes encoding the tumor necrosis factor receptors (p55 and p75) in the rat brain: a view from the blood-brain barrier. *Neuroscience* 93: 1449–1464, 1999.
84. **Nielsen S, Nagelhus EA, Amiry-moghaddam M, Bourque C, Agre P, Ottersen OP.** Specialized membrane domains for water transport in glial cells: high-resolution Immunogold dytochemistry of aquaporin-4 in rat brain. *J Neurosci* 17: 171–180, 1997.
85. **Noda M.** The subfornical organ, a specialized sodium channel, and the sensing of sodium levels in the brain. *Neuroscientist* 12: 80–91, 2006.
86. **Oldfield BJ, Badoer E, Hards DK, McKinley MJ.** Fos production in retrogradely labelled neurons of the lamina terminalis following intrvenous infusion of either hypertonic saline or angiotensin II. *Neuroscience* 60: 255–262, 1994.
87. **Oldfield BJ, Bicknell RJ, McAllen RM, Weisinger RS, McKinley MJ.** Intravenous hypertonic saline induces Fos immunoreactivity in neurons throughout the lamina terminalis. *Brain Res* 561: 151–156, 1991.
88. **Ono K, Honda E, Inenaga K.** Angiotensin II induces inward currents in subfornical organ neurones of rats. *J Neuroendocrinol* 13: 517–523, 2001.
89. **Paton JF, Waki H, Abdala AP, Dickinson J, Kasparov S.** Vascular-brain signaling in hypertension: role of angiotensin II and nitric oxide. *Curr Hypertens Rep* 9: 242–247, 2007.
90. **Peterson JR, Burmeister MA, Tian X, Zhou Y, Guruju MR, Stupinski JA, Sharma RV, Davisson RL.** Genetic silencing of Nox2 and Nox4 reveals differential roles of these NADPH oxidase homologues in the vasopressor and dipsogenic effects of brain angiotensin II. *Hypertension* 54: 1106–1114, 2009.
91. **Petrov T, Howarth AG, Krukoff TL, Stevenson BR.** Distribution of the tight junction-associated protein ZO-1 in circumventricular organs of the CNS. *Mol Brain Res* 21: 235–246, 1994.
92. **Pickel VM, Chan J, Ganten D.** Dual peroxidase and colloidal gold-labeling study of angiotensin converting enzyme and angiotensin-like immunoreactivity in the rat subfornical organ. *J Neurosci* 6: 2457–2469, 1986.
93. **Pulman KJ, Fry WM, Cottrell GT, Ferguson AV.** The subfornical organ: a central target for circulating feeding signals. *J Neurosci* 26: 2022–2030, 2006.
94. **Quan N, Stern EL, Whiteside MB, Herkenham M.** Induction of pro-inflammatory cytokine mRNAs in the brain after peripheral injection of subseptic doses of lipopolysaccharide in the rat. *J Neuroimmunol* 93: 72–80, 1999.
95. **Ratkovic S, Wagner GF, Ciriello J.** Distribution of stanniocalcin binding sites in the lamina terminalis of the rat. *Brain Res* 1218: 141–150, 2008.
96. **Richard D, Bourque CW.** Synaptic control of rat supraoptic neurones during osmotic stimulation of the organum vasculosum lamina terminalis in vitro. *J Physiol* 489: 567–577, 1995.
97. **Riediger T, Rauch M, Schmid HA.** Actions of amylin on subfornical organ neurons and on drinking behavior in rats. *Am J Physiol Regul Integr Comp Physiol* 276: R514–R521, 1999.
98. **Riediger T, Schmid HA, Lutz T, Simon E.** Amylin potently activates AP neurons possibly via formation of the excitatory second messenger cGMP. *Am J Physiol Regul Integr Comp Physiol* 281: R1833–R1843, 2001.
99. **Riediger T, Schmid HA, Young AA, Simon E.** Pharmacological characterisation of amylin-related peptides activating subfornical organ neurones. *Brain Res* 837: 161–168, 1999.
100. **Rogers KV, Dunn CK, Hebert SC, Brown EM.** Localization of calcium receptor mRNA in the adult rat central nervous system by in situ hybridization. *Brain Res* 744: 47–56, 1997.
101. **Rohmeiss P, Beyer C, Hocher B, Qadri F, Gretz N, Strauch M, Unger T.** Osmotically induced natriuresis and blood pressure response involves angiotensin $AT_1$ receptors in the subfornical organ. *J Hypertens* 13: 1399–1404, 1995.
102. **Rosas-Arellano MP, Solano-Flores LP, Ciriello J.** Co-localization of estrogen and angiotensin receptors within subfornical organ neurons. *Brain Res* 837: 254–262, 1999.
103. **Rowland NE, Fregly MJ, Han L, Smith G.** Expression of Fos in rat brain in relation to sodium appetite: furosemide and cerebroventricular renin. *Brain Res* 728: 90–96, 1996.
104. **Saavedra JM, Chevillard C.** Angiotensin-converting enzyme is present in the subfornical organ and other circumventricular organs of the rat. *Neurosci Lett* 29: 123–127, 1982.
105. **Saavedra JM, Israel A, Kurihara M, Fuchs E.** Decreased number and affinity of rat atrial natriuretic peptide (6–33) binding sites in the subfornical organ of spontaneously hypertensive rats. *Circ Res* 58: 389–392, 1986.
106. **Sato N, Ono K, Honda E, Haga K, Yokota M, Inenaga K.** Pilocarpine-induced salivation and thirst in conscious rats. *J Dent Res* 85: 64–68, 2006.
107. **Schmid HA, Rauch M, Koch J.** Effect of calcitonin on the activity of ANG II-responsive neurons in the rat subfornical organ. *Am J Physiol Regul Integr Comp Physiol* 274: R1646–R1652, 1998.
108. **Shimizu H, Watanabe E, Hiyama TY, Nagakura A, Fujikawa A, Okado H, Yanagawa Y, Obata K, Noda M.** Glial $Na_x$ channels control lactate signaling to neurons for brain $[Na^+]$ sensing. *Neuron* 54: 59–72, 2007.
109. **Simpson JB.** The circumventricular organs and the central actions of angiotensin. *Neuroendocrinology* 32: 248–256, 1981.
110. **Simpson JB, Routenberg A.** Subfornical organ: site of drinking elicitation by angiotensin II. *Science* 181: 1172–1174, 1973.
111. **Simpson JB, Routtenberg A.** The subfornical organ and carbachol-induced drinking. *Brain Res* 45: 135–152, 1972.
112. **Simpson JB, Routtenberg JB.** Subfornical organ lesions reduce intravenous angiotensin-induced drinking. *Brain Res* 88: 154–161, 1975.
113. **Sinnayah P, Lazartigues E, Sakai K, Sharma RV, Sigmund CD, Davisson RL.** Genetic ablation of angiotensinogen in the subfornical organ of the brain prevents the central angiotensinergic pressor response. *Circ Res* 99: 1125–1131, 2006.
114. **Smith PM, Beninger RJ, Ferguson AV.** Subfornical organ stimulation elicits drinking. *Brain Res Bull* 38: 209–213, 1995.
115. **Smith PM, Chambers AP, Price CJ, Ho W, Hopf C, Sharkey KA, Ferguson AV.** The subfornical organ: a central nervous system site for actions of circulating leptin. *Am J Physiol Regul Integr Comp Physiol* 296: R512–R520, 2009.
116. **Smith PM, Ferguson AV.** Vasopressin acts in the subfornical organ to decrease blood pressure. *Neuroendocrinology* 66: 130–135, 1997.

117. **Smith PM, Rozanski G, Ferguson AV.** Acute electrical stimulation of the subfornical organ induces feeding in satiated rats. *Physiol Behav* 99: 534–537, 2010.
118. **Smith PM, Samson WK, Ferguson AV.** Cardiovascular actions of orexin-A in the rat subfornical organ. *J Neuroendocrinol* 19: 7–13, 2007.
119. **Starbuck EM, Fitts DA.** Influence of salt intake, ANG II synthesis and SFO lesion on thirst and blood pressure during sodium depletion. Subfornical organ. *Appetite* 31: 309–331, 1998.
120. **Summerlee AJ, O'Byrne KT, Jones SA, Eltringham L.** The subfornical organ and relaxin-induced inhibition of reflex milk ejection in lactating rats. *J Endocrinol* 115: 347–353, 1987.
121. **Summerlee AJS, Wilson BC.** Role of the subfornical organ in the relaxin induced prolongation of gestation in the rat. *Endocrinology* 134: 2115–2120, 1994.
122. **Sun K, Ferguson AV.** Cholecystokinin activates area postrema neurons in rat brain slices. *Am J Physiol Regul Integr Comp Physiol* 272: R1625–R1630, 1997.
123. **Sunn N, Egli M, Burazin TC, Burns P, Colvill L, Davern P, Denton DA, Oldfield BJ, Weisinger RS, Rauch M, Schmid HA, McKinley MJ.** Circulating relaxin acts on subfornical organ neurons to stimulate water drinking in the rat. *Proc Natl Acad Sci USA* 99: 1701–1706, 2002.
124. **Takahashi Y, Smith PM, Ferguson AV, Pittman QJ.** Circumventricular organs and fever. *Am J Physiol Regul Integr Comp Physiol* 273: R1690–R1695, 1997.
125. **Takayama K, Johno Y, Hayashi K, Yakabi K, Tanaka T, Ro S.** Expression of c-Fos protein in the brain after intravenous injection of ghrelin in rats. *Neurosci Lett* 417: 292–296, 2007.
126. **Tanaka J, Kariya K, Miyakubo H, Sakamaki K, Nomura M.** Attenuated drinking response induced by angiotensinergic activation of subfornical organ projections to the paraventricular nucleus in estrogen-treated rats. *Neurosci Lett* 324: 242–246, 2002.
127. **Tanaka J, Kariya K, Nomura M.** Angiotensin II reduces serotonin release in the rat subfornical organ area. *Peptides* 24: 881–887, 2003.
128. **Tanaka J, Miyakubo H, Okumura T, Sakamaki K, Hayashi Y.** Estrogen decreases the responsiveness of subfornical organ neurons projecting to the hypothalamic paraventricular nucleus to angiotensin II in female rats. *Neurosci Lett* 307: 155–158, 2001.
129. **Tanaka J, Okumura T, Sakamaki K, Miyakubo H.** Activation of serotonergic pathways from the midbrain raphe system to the subfornical organ by hemorrhage in the rat. *Exp Neurol* 169: 156–162, 2001.
130. **Thornton SN, Fitzsimons JT.** The effects of centrally administered porcine relaxin on drinking behavior in male and female rats. *J Neuroendocrinol* 7: 165–169, 1995.
131. **Thunhorst RL, Beltz TG, Johnson AK.** Effects of subfornical organ lesions on acutely induced thirst and salt appetite. *Am J Physiol Regul Integr Comp Physiol* 277: R56–R65, 1999.
132. **Thunhorst RL, Fitts DA, Simpson JB.** Angiotensin-converting enzyme in subfornical organ mediates captopril-induced drinking. *Behav Neurosci* 103: 1302–1310, 1989.
133. **Voisin DL, Simonian SX, Herbison AE.** Identification of estrogen receptor-containing neurons projecting to the rat supraoptic nucleus. *Neuroscience* 78: 215–228, 1997.
134. **Wall KM, Ferguson AV.** Endothelin acts at the subfornical organ to influence the activity of putative vasopressin and oxytocin-secreting neurons. *Brain Res* 586: 111–116, 1992.
135. **Wall KM, Nasr M, Ferguson AV.** Actions of endothelin at the subfornical organ. *Brain Res* 570: 180–187, 1992.
136. **Wang H, Wang ZA, He RR.** [Modulatory effects of 17β-estradiol on the electrical activity of subfornical organ neurons]. *Sheng Li Xue Bao* 52: 515–518, 2000.
137. **Washburn DLS, Beedle AM, Ferguson AV.** Inhibition of subfornical organ neuronal potassium channels by vasopressin. *Neuroscience* 93: 349–359, 1999.
138. **Washburn DLS, Smith PM, Ferguson AV.** Control of neuronal excitability by an ion sensing receptor. *Eur J Neurosci* 11: 1947–1954, 1999.
139. **Weisinger RS, Stanley TK, Begg DP, Weisinger HS, Spark KJ, Jois M.** Angiotensin-converting enzyme inhibition lowers body weight and improves glucose tolerance in C57BL/6J mice maintained on a high fat diet. *Physiol Behav* 98: 192–197, 2009.
140. **Wolburg H, Liebner S, Lippoldt A.** Freeze-fracture studies of cerebral endothelial tight junctions. *Methods Mol Med* 89: 51–66, 2003.
141. **Xia Y, Krukoff TL.** Cardiovascular responses to subseptic doses of endotoxin contribute to differential neuronal activation in rat brain. *Brain Res Mol Brain Res* 89: 71–85, 2001.
142. **Zimmerman MC, Dunlay RP, Lazartigues E, Zhang Y, Sharma RV, Engelhardt JF, Davisson RL.** Requirement for Rac1-dependent NADPH oxidase in the cardiovascular and dipsogenic actions of angiotensin II in the brain. *Circ Res* 95: 532–539, 2004.
143. **Zimmerman MC, Lazartigues E, Lang JA, Sinnayah P, Ahmad IM, Spitz DR, Davisson RL.** Superoxide mediates the actions of angiotensin II in the central nervous system. *Circ Res* 91: 1038–1045, 2002.