

ISSN 1669-5402 (Print)

ISSN 1669-5410 (Online)



*Physiological  
Mini-  
Reviews*

*Edited by the Argentine Physiological Society.*

*Vol. 5, N° 5, October - November 2011.*

<http://www.mini.reviews.safisiol.org.ar>

# Physiological Mini-Reviews

[ISSN 1669-5402 (Print); ISSN 1669-5410 (Online)]

Edited by **the Argentine Physiological Society**

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(Resol. IGJ 763-04)

# The renin angiotensin system in the central nervous system.

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## INTRODUCTION

The first evidences indicating that angiotensin II (ANG II) was a peptide with action on the brain were shown in 1961 when it was found that the intraventricular injection of ANG II induces a centrally mediated pressor response (1). As a neuropeptide, ANG II belongs to the class of neuromodulators. The brain renin angiotensin system (RAS) exerts paracrine, autocrine and intracrine functions independently of circulating blood-borne ANG II which has a limited access to the brain by the blood-brain barrier (BBB) in the circumventricular organs (CVOs) (2). Brain-generated ANG II controls several physiological processes like stimulation of thirst, water intake and sodium appetite, acting as a neurotransmitter in neurons of brain areas such as the Subfornical organ (SFO) and Organum vasculosum of the lamina terminalis (OVLT). Generated angiotensins (ANGs) at the central nervous system (CNS) also stimulate endocrine secretions like arginine-vasopressin (AVP), oxytocin (OT), corticotrophin-releasing hormone (CRH) and adenocorticotrophin (ACTH secretion). Brain ANG II modulates the sympathetic autonomic functions and regulates blood pressure by increasing AVP and ACTH secretion and modulating the baroreceptor reflex and the sympathetic output (3). During the last decade it has been established that, apart from its classical actions, ANG II exhibits other effects induced by direct action on its receptors or via local effects of its metabolites (4). Thereby, central actions of ANGs are not exclusively associated with their traditional roles. Indeed, several studies have shown that central ANGs are also involved in sexual behavior, stress, learning, and memory (5).

The endogenous brain RAS modulates the hypothalamic-pituitary-adrenal axis through the synthesis and secretion control of hypothalamic releasing factors. It also regulates cardiovascular function and hydromineral balance through modulation of water and sodium intake and controlling thirst, salt appetite and water excretion, overlapping many of ANG II peripheral effects. Brain RAS stimulates central autonomic nervous sympathetic activity, controlling central and peripheral sympathoadrenal systems and regulating neuronal norepinephrine (NE) neurotransmission and, as a derived action of this, brain and body temperature. Brain ANG II also controls the diurnal rhythms, modulating serotonin transmission by stimulation of neuronal serotonin synthesis and release. The central RAS may be involved in the regulation of multiple additional functions in the brain, which are not completely established, including brain development, neuronal migration, processes of sensory information, cognition, learning, retention and memory, regulation of emotional responses, sexual behaviour, apoptosis as well as the cerebral blood flow (6).

On the other hand, new peptides have been identified as metabolic products of ANG II, like the heptapeptide ANG III (fragment 2-8), the hexapeptide ANG IV (fragment 3-8) and the heptapeptide ANG 1-7 (fragment 1-7). These members of the ANG family are biologically active peptides formed in the CNS and play different roles in the brain as neurotransmitters, exciting neurons with high specificity and also as neuroendocrine, paracrine, autocrine and intracrine factors. Finally, other members like ANG fragments 3-7, 1-9 and 2-10 are relatively poorly known and further research will be needed in order to elucidate their physiological roles (7). Figure 1 summarizes the current overview of the brain RAS.

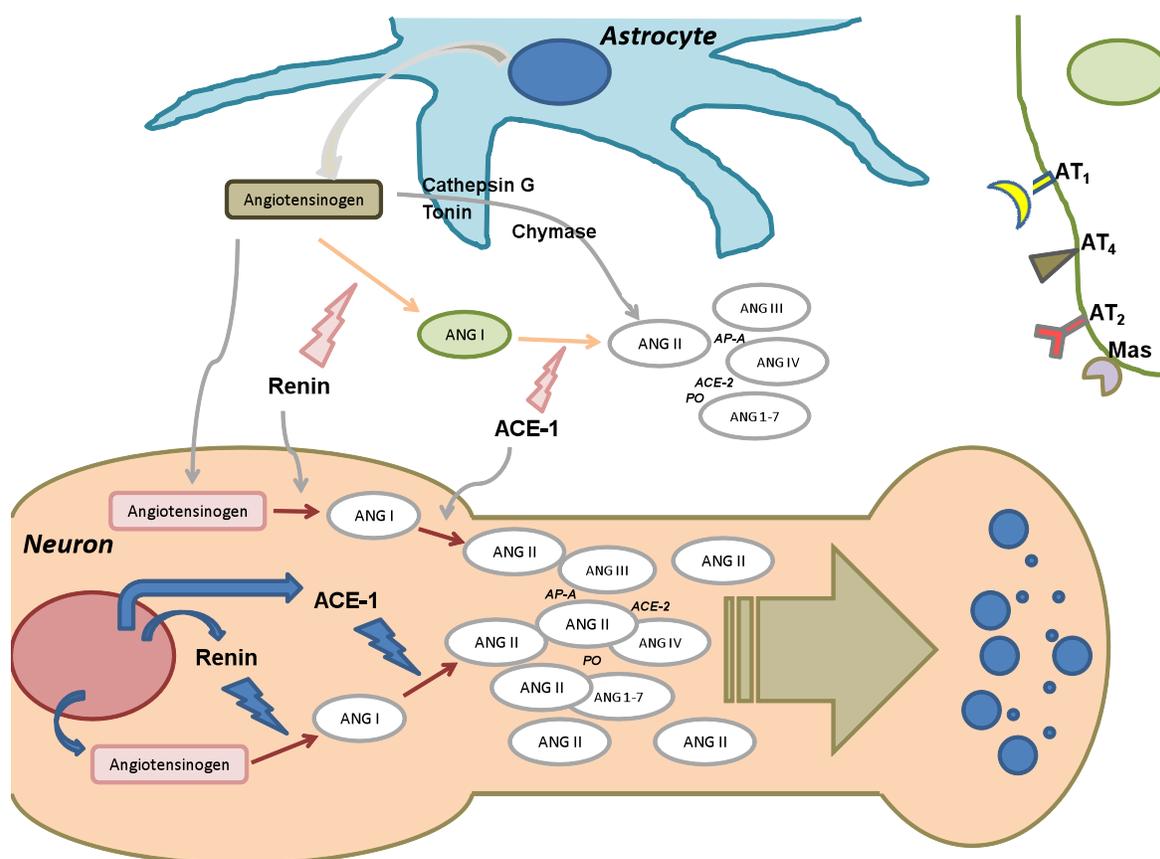


Figure 1. Intraneuronal and extraneuronal synthesis of angiotensin fragments in the brain. ACE: angiotensin converting enzyme; AP-A: aminopeptidase A; PO: propyloligopeptidase. AT<sub>1</sub>, AT<sub>2</sub>, AT<sub>4</sub>, Mas: angiotensin postsynaptic receptors. Adapted from Paul M. et al., *Physiol Rev* 86:747, 2006.

## PHYSIOLOGICAL ACTIONS OF ANGIOTENSIN II IN THE CNS

Two mechanisms have been proposed to explain central actions of ANG II. Brain ANG II receptors located in neurons inside the BBB can be stimulated either by ANG II generated in the brain or circulating ANG of peripheral origin as well, and transported into



- alcohol intake, via dopaminergic interaction
- stress brain response, including stress-induced gastric injury
- vasoconstriction of cerebral arterioles
- neuronal norepinephrine release and turnover and norepinephrine-mediated neuromodulation
- L and T type calcium channels
- visual and somatosensory areas in thalamus
- anxiety
- inflammation

Brain AT<sub>1</sub> receptors induce inhibition of:

- K<sup>+</sup> channels
- GABA and glutamatergic transmission
- long term potentiation of synaptic plasticity
- neuronal NE uptake
- NMDA (N-methyl-D-aspartate)-induced neuronal stimulation

The function of AT<sub>2</sub> receptors remains controversial. AT<sub>2</sub> receptors counterbalance some of the biological effects of AT<sub>1</sub> receptor signalling on vascular resistance and antinatriuretic effects.

AT<sub>2</sub> receptors may also decrease the sensitivity to pain, while they exacerbate several other neuronal activities such as:

- ionic currents
- cell differentiation
- axonal regeneration after nerve crush
- modulation of programmed cell death (growth inhibition and promotion of apoptosis)
- transient K<sup>+</sup> current. Reduces the length of action potentials and the refractory period leading to an increase in membrane excitability
- acquisition of conditional avoidance responses
- growth arrest
- cell migration
- cerebral circulation and cerebrovascular development
- blood flow to basal forebrain and pituitary gland
- β endorphin secretion
- body temperature

Figure 2 summarizes the main actions of ANG II at the CNS.

### **Body fluid homeostasis, sodium and water balance, dipsogenic action and arginine-vasopressin secretion**

ANG II regulates body fluids, stimulating thirst and salt appetite (via AVP and CRH-ACTH-glucocorticoids secretion) in the hypothalamus, and inhibiting natriuresis and diuresis (via AVP secretion). The MePON, SFO and OVLT contain AT<sub>1</sub> and volume-receptors and osmoreceptors for control, regulation and homeostasis of body fluids (8).

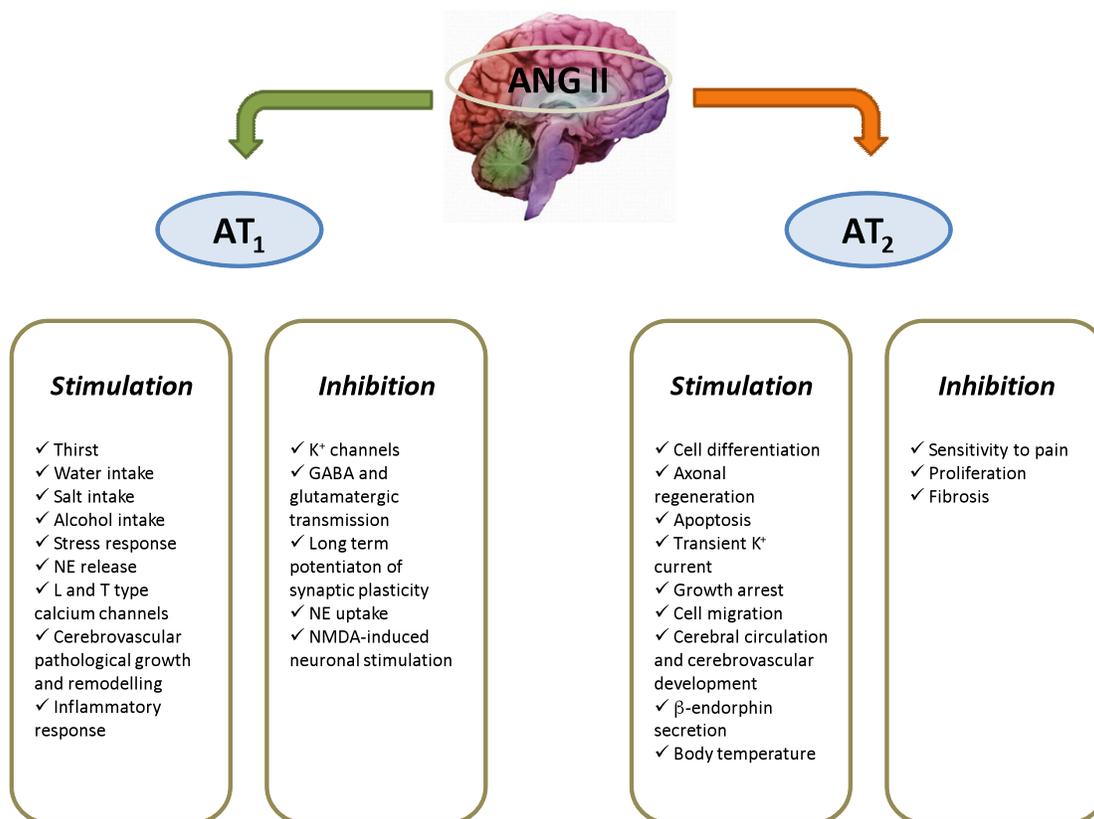


Figure 2. Main actions of Angiotensin II on Central Nervous System. NE: norepinephrine; NMDA: N-methyl-D-aspartate.

### Regulation of sympathetic tone and activity and control of cardiovascular function and blood pressure

Brain ANG II modulates the sympathetic tone in the hypothalamus, brainstem and medulla. Indirect effects are exerted on the anterior hypothalamus where ANG II regulates NE transmission and sympathetic activity and stimulates AVP and CRH secretion (9,10). Brain ANG regulates the cardiovascular function and blood pressure. ANG II increases blood pressure through sympathetic activation, AVP, CRH and ACTH secretion and decreases sympathetic baroreceptor sensitivity by means of AT<sub>1</sub> receptors activation in the NTS (11). Moreover, enhanced central sympathetic activity results in an increase in vasoconstrictor activity (12). In this way ANG II induces tonic sympathoexcitatory effects through AT<sub>1</sub> receptor stimulation of glutamatergic neurons and sympathoinhibitory effects via GABAergic neurons in the rostral ventrolateral medulla, the brainstem 'pressor area' (13).

Brain generated ANG II acts as neuromodulator or a neurotransmitter in order to process and sense the afferent information received from baroreceptors in diverse nuclei associated with cardiovascular control (6,9,12). ANG II modulates neuronal activity through AT<sub>1</sub> or AT<sub>2</sub> receptors, changing the activity of membrane ionic currents and channels in areas implied in blood pressure regulation, like the locus coeruleus, the hypothalamic PVN and the NTS where ANG II receptors receive afferent terminals from

the dorsal motor nucleus of the vagus, the rostral and caudal ventrolateral medulla and the intermediolateral cell column of the spinal cord (14,15).

### **Catecholaminergic, serotonergic, GABAergic and glutamatergic neurotransmission**

Brain RAS and catecholamines (NE, epinephrine, dopamine) are co-localized in several areas of the CNS, including several nuclei of the forebrain (mainly hypothalamic nuclei) and the brainstem (i.e., the NTS). Both ANG II and ANG III stimulate central sympathetic activity regulating NE neurotransmission at the presynaptic nerve ending level. There is an inverse relationship between ANG II circulating levels and NE content in the CNS. ANG II increases spontaneous release and potassium or acetylcholine NE-evoked release, and decreases NE neuronal uptake in hypothalamus and medulla oblongata (10). These effects are not tissue-specific as they were shown in different areas of the CNS. ANG II increases NE content in subcellular granular stores and decreases it in cytoplasmic neuronal compartments, diminishes NE turnover and enhances NE neuronal synthesis, transporter (NET), tyrosine-hydroxylase expression and dopamine  $\beta$ -hydroxylase mRNA transcription. All these actions result in an enhanced NE availability at the synaptic gap, with the consequent increase in sympathetic activity. ANG II also stimulates MAO activity in hypothalamus (10,16). AT<sub>1</sub> receptors mediate ANG II effects on NE neurotransmission, while AT<sub>2</sub> receptors are not involved (17). ANG II effects on NE uptake in the CNS are reversed by low and non-effective doses of ANP (10).

AT<sub>1</sub> receptors located pre-and postsynaptically may influence norepinephrinergic, GABAergic, and/or glutamatergic transmission (18-20). ANG II stimulates spinally projecting neurons in the PVN by attenuation of GABAergic synaptic inputs (21) and inhibits NMDA receptor (N-methyl-D-aspartate)-induced neuronal stimulation in the amygdale (22). ANG II increases GABA (B) receptor expression and augments GABA (B) receptor-mediated responses in the NTS, contributing to central ANG actions that result in dampening of baroreflexes and elevation of arterial blood pressure (23). Figure 3 shows ANG II effects on central neurotransmission.

### **Atrial natriuretic peptide**

ANP, BNP and CNP are synthesized and released in the CNS. There is a strong correlation between ANP and ANG II and their respective receptors localization in the CNS. These natriuretic peptides are the physiological antagonists of brain RAS and exhibit opposite effects to ANG II on neuronal NE uptake, release, endogenous content and turnover in the hypothalamus. ANP also opposes to ANG II-induced increase in MAO activity and inhibits ANG II-induced water intake in the brain as well as ANG II stimulated secretion of CRH, AVP and OT (10).

### **Development and neuronal growth, differentiation, proliferation, regeneration and apoptosis**

ANG II acts through AT<sub>1</sub> receptors as a growth factor and promotes protein synthesis and fibroblast proliferation (24). During the embryonic life, AT<sub>2</sub> receptors are mainly located in areas closely related with the development, and their number, decreases after birth (24). In adults, AT<sub>2</sub> receptors are found in areas related to sensory and motor control and integration, visual pathways, limbic system activity and behavior. AT<sub>2</sub> receptors promote axonal regeneration after nerve crush (25), growth arrest and cell migration. Moreover, AT<sub>2</sub> activation modulates programmed cell death by the inhibition of

growth and apoptosis promotion through activation of MAP kinases (10), promotes nerve generation and neuronal differentiation in cells of neuronal origin, through an increase in NO production and mediates anti-proliferative effects in different cells lines (10).

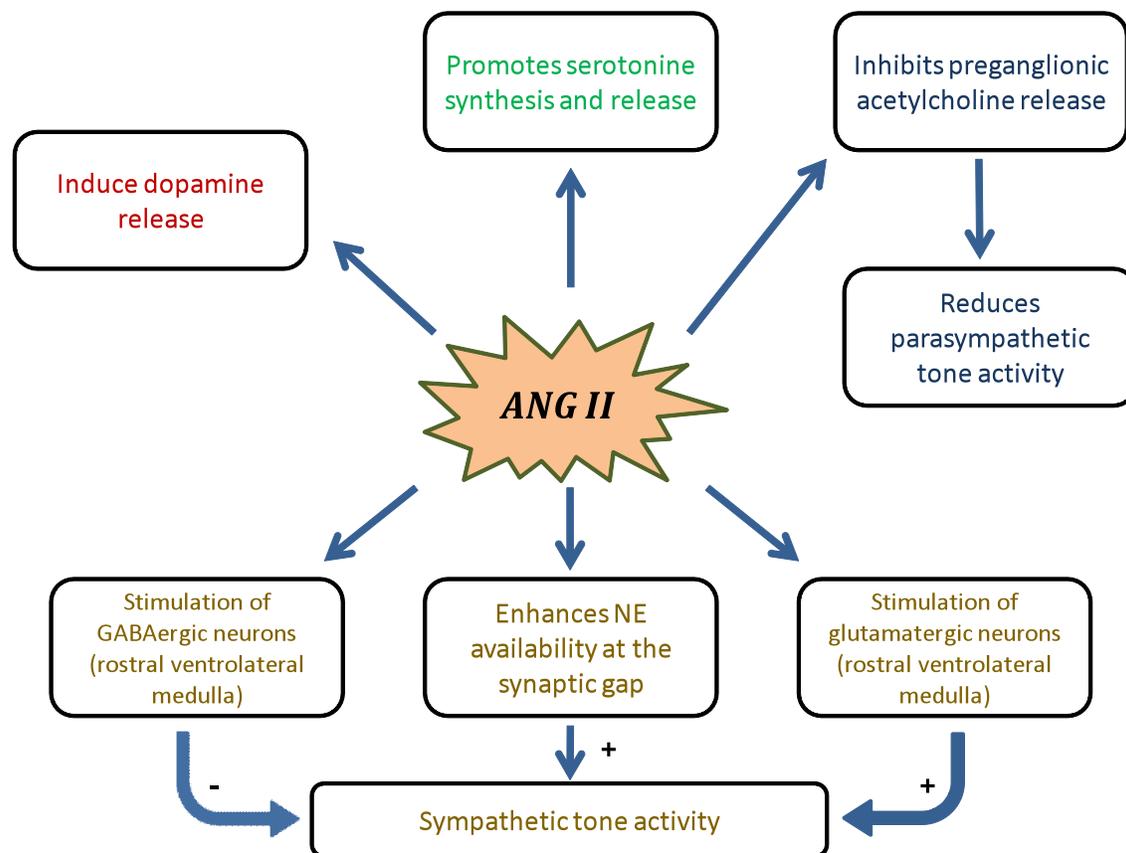


Figure 3. Effects of Angiotensin II on diverse neurotransmission systems (mainly mediated by  $AT_1$  receptors). NE: norepinephrine.

### Neuronal ion channels and excitability

ANG II regulates ionic currents in neuronal tissues.  $AT_1$  and  $AT_2$  stimulation cause opposite effects on calcium and potassium channels.  $AT_1$  stimulation enhances calcium release from intracellular stores and its influx from the extracellular space, increasing intracellular calcium in astroglial cells. In hypothalamus and brain stem areas, ANG II increases the neuronal firing rate, which involves the inhibition of the delayed rectifier potassium current. On the other hand, ANG II stimulates both, transient  $K^+$  current and delayed-rectifier  $K^+$  current via  $AT_2$  receptors in brain stem neurons (10).  $AT_2$ -induced activation of transient potassium currents is associated with a reduction in the length of action potentials and a shortening of the refractory period, which lead to an increase in membrane excitability (26).  $AT_2$  activation also lowers body temperature. This effect could be related to the increase in membrane excitability of neurons associated to body temperature control, as well as to vasodilation of cerebral vessels in hypothalamic areas.

Moreover, activation of AT<sub>2</sub> increases the firing rate in thalamus and amygdala, suggesting that GABA A receptors are involved in ANG-II-induced effects on neuronal activity (10).

### **Cognition, memory, behavior and emotion. Motor and somatosensory control**

Brain ANG II influences cognitive functions, emotional processes and behavioral changes by acting on specific AT<sub>1</sub> receptors. Treatment with ANG II receptor blockers prevents amyloid beta deposition in the brain and attenuate cognitive impairment in elderly individuals and in Alzheimer disease (27).

In the hippocampus, stimulation of AT<sub>1</sub> and/or AT<sub>2</sub> receptors blocks memory formation, retention and consolidation (28,29). Conversely, ANG II facilitates learning and consolidation of retention and memory, probably through ANG IV formation which interacts with GABA neurotransmission (10). Thus, different responses might be obtained depending on the time intervals between ANG II injection and the behavioral paradigm tested.

Brain administration of ANG II blocks long-term potentiation induction of synaptic plasticity in the amygdala, a specific process of behavioral significance related to learning and memory (10,29). This inhibition is related to presynaptic ANG II action on glutamatergic terminals and with postsynaptic inhibition of NMDA receptors (30,31). The inhibition of AT<sub>2</sub> abolishes the ANG-II-induced acquisition of conditioned avoidance responses (32). The AT<sub>2</sub>-mediated increase of neuronal firing rate seems to involve lipoxygenase metabolites of arachidonic acid generation and serine/threonine phosphatase type 2A activation. ANG II up-regulates AT<sub>2</sub> mRNA levels in rat cortical neurons, through regulation of serine/threonine phosphatases activity (10). Taken together, these findings support the hypothesis that, in addition to their role during development, AT<sub>2</sub> receptors may also be involved in cognitive processes in the adult and modulate behavioral effects, mood and pain threshold, and indicate a critical role of ANG II in cognitive impairment associated with vascular disease, Alzheimer disease, metabolic syndrome and other neurodegenerative diseases (27).

In addition, ANG II increases firing rates in the visual and somatosensory thalamus, in the hippocampus and in the superior colliculus and induced neuronal excitation in the inferior olivary nucleus suggesting that it has a role in information processing and in control of locomotor activity. Brain RAS is also involved in sensitivity control. Stimulation of AT<sub>2</sub> decreases the sensitivity to pain and augments  $\beta$  endorphin secretion (10,25).

### **Anxiety-Alcohol consumption**

AT<sub>1</sub> stimulation increases anxiety. This effect is mediated by ANG II interaction with benzodiazepine receptors and by increasing prazosin-binding sites in the amygdala. Conversely, AT<sub>2</sub> receptors stimulation decreases anxiety (33). AT<sub>1</sub> also stimulate alcohol consumption in the CNS, reducing dopamine concentration in the ventral tegmental area, supporting a role for dopaminergic transmission in ANG-II-induced alcohol preference (34).

### **Cerebrovascular flow. Stroke. Protection against ischemia**

ANG II regulates cerebral blood flow, exerting vasoconstriction which favors ischemia and cerebral stroke. AT<sub>1</sub> over-stimulation exacerbates cerebrovascular pathological growth and remodelling with inflammatory reaction in cerebral blood vessels and decreased compliance, impaired cerebral autoregulation, increased cerebrovascular

eNOS/iNOS ratio and NO formation. Centrally AT<sub>1</sub> blockers normalize cerebrovascular flow, decreasing macrophage infiltration and TNF- $\alpha$ , interleukin-1 $\beta$  and NF $\kappa$ - $\beta$  expression in microvessels in hypertensive rats. AT<sub>1</sub> blockade in SHR rats decreases brain vulnerability to ischemia and neuronal death during experimental stroke and reduces the size of the infarct after occlusion of cerebral arteries. Then, treatment with AT<sub>1</sub> antagonists may be useful for prevention of ischemia and inflammatory diseases of the brain (35,36).

AT<sub>2</sub> receptors also contribute to the autoregulation of cerebrovascular resistance and blood flow. The decreased number of AT<sub>2</sub> in aged rats can be involved in the pathophysiology of cerebrovascular dysfunction. AT<sub>2</sub> stimulation induces cerebrovascular angiogenesis and vasodilation and augments circulation and blood flow to the forebrain and pituitary gland by mean of NO and prostacyclins release during hemorrhagic hypotension in rats. ANG II also alters BBB permeability through prostaglandins release, allowing the transport of substances across the cerebral capillary endothelium (35,37). Therefore, ANG II exerts stroke-protective effects through stimulation AT<sub>2</sub> receptors. ANG II receptor blockers exert a dual influence, since AT<sub>1</sub> blockade decreases local vasoconstriction, allowing free ANG II to stimulate the unoccupied AT<sub>2</sub> receptor and increase local vasodilation, diminishing local brain ischemia and the volume and extent of brain damage (38,39).

### **Control of hormone secretion. Hypothalamus, hypophysis and adrenal glands**

Brain ANG II controls reproductive function and the hypothalamic-pituitary-adrenal axis and increases NE release in the hypothalamus. Considering that NE stimulates hypothalamic releasing factors, brain ANG II may control the anterior pituitary lobe secretion by means of NE-dependent indirect regulation of hypothalamic releasing factors formation and release from de median eminence to the pituitary portal circulation, in order to exert their effects on the hypophysis. Moreover, the complete RAS is present in the anterior pituitary lobe, where ANG II is detected in gonadotrophic (co-localized with LH), lactotrophic, corticotrophic and probably thyrotrophic cells (6).

### **CRH-ACTH –Glucocorticoids cascade and stress**

ANG II is involved in the regulation of adrenocortical hormones, by modulating the synthesis and release of CRH, ACTH and glucocorticoid levels (10). ANG II regulates ACTH secretion, either directly at the pituitary gland or indirectly by increasing CRH or AVP synthesis and release from the hypothalamic PVN (29). ACTH release is also increased by stimulation of ANG II receptors placed outside the BBB in the SFO. ANG II effects on CRH synthesis takes place in the parvocellular PVN and CRH release is produced in the median eminence (10).

Brain ANG II and AT<sub>1</sub> receptors increase during stress and produce anxiety. Brain AT<sub>1</sub> blockade reduces anxiety and prevents ANG II-induced hormonal and sympathoadrenal response to stress, like the increase in CRH release and the consequent augment of ACTH and glucocorticoids secretion and also prevents the ulcerations of the gastric mucosa produced by stress, by preserving gastric blood flow and avoiding inflammation (40).

### **Mineralocorticoids**

A feedback mechanism between brain RAS, sodium levels and mineralocorticoids was described. ANG II controls salt appetite and sodium excretion and conversely, plasma

sodium and mineralocorticoids up-regulate central ANG II receptors. Aldosterone and deoxycorticosterone cross the BBB enhancing ANG II induction on sodium appetite and dipsogenic action, as a result of an increase in brain AT<sub>1</sub> receptor number at the PVN, MePON, SFO, NTS and AP (6).

### **Prolactin, Gonadotrophins, LH secretion**

Brain ANG II controls the reproductive function since it stimulates oxytocin, LHRH, LH and reduces prolactin release. Central ANG II inhibits pituitary prolactin release indirectly via modulation of dopaminergic activity in the arcuate nucleus. This process depends on estrogen and progesterone levels. Moreover, ANG II can be an intermediate of LHRH on pituitary LH secretion. Since ANG II and LHRH are co-localized in OVLN neurons, ANG II may release NE, enhancing LHRH secretion and thus, indirectly, stimulating LH secretion. AT<sub>1B</sub> receptors located in pituitary lactotrophic and corticotrophic cells stimulate PLC activity and IP<sub>3</sub> and diacylglycerol (DAG) formation, suggesting a direct paracrine action of ANG II on the anterior hypophyseal lobe. During pregnancy, elevated plasma levels of ANG II may contribute to increase sympathetic nerve activity and attenuate baroreflex gain markedly in this condition (9,10).

### **Sexual hormones. Estrogens, progesterone and androgens**

Pituitary anterior lobe RAS is under the control of sexual hormones. The number of AT<sub>1</sub> receptors changes during the oestrous cycle, being high during metaestrus, decreases during oestrus and diestrus, attaining the lower during proestrus. In addition, AT<sub>1</sub> receptors are very low in male and ovariectomized female rats. 17 $\beta$ -estradiol and progesterone treatment increases AT<sub>1A</sub>-mRNA expression in tyrosine hydroxylase synthesizing neurons of the dorsal arcuate nucleus, but decreases the expression in the MePON and anterior pituitary. This explains why estrogens diminish some central ANG II effects. On the other hand, androgens increase renin activity and ANG II synthesis in the anterior pituitary lobe (10).

### **Growth hormone**

Pituitary ANG II decreases growth hormone (GH) secretion by a direct action on somatotrophic cells of the hypophysis (36).

### **Vasopressin and oxytocin**

Brain ANG II stimulates AVP and OT synthesis (in the hypothalamus) and secretion (in the posterior pituitary lobe). These effects can be exerted at different levels: a) as a paracrine effect in the hypothalamic nuclei PVN and SON; b) from the median eminence to the portal blood vessels and c) in the posterior pituitary lobe, from the neural terminals of the hypothalamic-hypophyseal tract. AVP synthesis and secretion are exerted mainly in magnocellular neurons of the PVN, where most of AT<sub>1</sub> receptors are located. Moreover, the presence of angiotensinogen, renin, ACE, ANG II and its receptors have been described in the posterior lobe but the functionality of the RAS system in these areas has not been clarified (6).

### **Vision system**

In the superior colliculus, ANG II-AT<sub>1</sub> activation markedly reduces the amplitude of visual evoked potentials, and AT<sub>2</sub> binding decreased after bilateral eye enucleation, suggesting that ANG II receptors may be regulated by retinal inputs (10,25).

### **Hypertension**

Higher expression and exacerbated activity of the brain RAS components may play a role in the pathogenesis and development of hypertension in several experimental models of hypertension, as in genetically spontaneously hypertensive rats (SHR), DOCA-salt, Goldblatt 2K-1C, sino-aortic denervated and pregnancy-induced hypertension. Hypertensive states exhibit an enhanced response to ANG II, a decreased catabolism of the peptide and increased ANG II receptors in selected brain and brainstem areas, as it was shown in SHR rats (2,35,36,41). The sino-aortic denervated rat shows enhanced ANG II binding sites in the anterior pituitary. In addition, ANG II receptors are increased in brain nuclei and areas (MePON, SFO, PVN, NTS and AP) of DOCA-salt hypertensive rats. AT<sub>1</sub> stimulation attenuates the hypotensive action of central  $\alpha_2$  receptors and stimulates  $\beta$  adrenoceptors, increasing collagen synthesis and deposition on brain microvessels. Consequently, ANG microinjection in the NTS causes hypertension and inhibition of the baroreflex. The enhanced pressor response to ANG II injection observed in the hypothalamus of fructose-induced hypertensive rats is mediated by stimulation of  $\beta_1$  adrenoceptors and attributed to increased AT<sub>1</sub> and  $\beta_1$  receptors tone (10,42).

### **Inflammation**

Stimulation of AT<sub>1</sub> receptors, colocalized with NAD(P)H oxidase in NTS neurons, induces local reactive oxygen species production and the development of inflammation (41). The RAS plays a pivotal role in autoimmune inflammation of the CNS, being its blockade a potential new target for multiple sclerosis therapy. In this way, the renin inhibitor aliskiren, the ECA inhibitor enalapril, or the preventive/therapeutic administration of AT<sub>1</sub> antagonist losartan, strongly ameliorated the course of multiple sclerosis (43).

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