Evidence Supporting a Functional Role for Intracellular Renin in the Brain

Julie L. Lavoie, Xuebo Liu, Robert A. Bianco, Terry G. Beltz, Alan Kim Johnson, Curt D. Sigmund

Abstract—The brain renin–angiotensin system is implicated in the regulation of blood pressure (BP) and fluid homeostasis. Recent studies reveal that 2 forms of renin are expressed in the brain of rodents and humans: secreted prorenin and a nonsecreted intracellular form of active renin (icREN). Although the intracellular action of renin has long been postulated, no data supporting its role in BP regulation has been reported. Therefore, we directly evaluated whether this form of renin has physiological implications for BP regulation by characterizing transgenic mice expressing human icREN driven by the glial fibrillary acidic protein (GFAP) promoter and comparing it with similar mice expressing the secreted form of renin. GFAP-icREN mice express hREN primarily in the brain and at the same level of expression as GFAP-secreted prorenin. Unlike the secreted form, which can be detected in cerebrospinal fluid, no human renin could be detected in the cerebrospinal fluid of GFAP-icREN mice. GFAP-icREN mice were then bred with transgenic mice expressing human angiotensinogen, also driven by the GFAP promoter. Double-transgenic mice expressing either the intracellular renin (2.0±0.12 mL/10 g/day) or secreted renin (2.8±0.3 mL/10 g/day) exhibited an increase in drinking volume compared with nontransgenic littermates (1.5±0.1 mL/10 g/day). Both models exhibited an increase in mean arterial pressure (137±5 and 133±8 mm Hg, respectively) compared with control littermates (115±3 mm Hg), which could be rapidly reduced after ICV injection of losartan. These data support the concept of an intracellular form of renin in the brain, which may provoke functional changes in fluid homeostasis and BP regulation. (Hypertension. 2006;47:461-466.)

Key Words: renin-angiotensin system • brain

The renin–angiotensin system (RAS) is well known for its effects on blood pressure (BP) and fluid homeostasis. Although these actions were long thought to be caused primarily by the circulating RAS, in the past decade, it has become apparent that local RAS have an important physiological role. For instance, all components of the RAS are present in the heart, kidney, adrenal gland, and brain (reviewed in Reference 1). It is now becoming clear that cells expressing renin and angiotensinogen (AGT) are in close proximity to each other and to cells expressing angiotensin type 1 (AT1) receptors in a number of tissues including the brain.2,3 This suggests the potential for local synthesis and action of angiotensin independent of its production in the systemic circulation. In addition, some cells in the brain coexpress both proteins.3 This has led us and others to question whether the RAS can function intracellularly either through the intracellular production or intracellular action of angiotensin II (Ang II). Interestingly, the intracellular action of Ang II was proposed as early as 1971 when Robertson and Khairallah4 reported nuclear localization of the peptide in its effects on blood pressure (BP) and fluid homeostasis. Although these actions were long thought to be caused primarily by the circulating RAS, in the past decade, it has become apparent that local RAS have an important physiological role. For instance, all components of the RAS are present in the heart, kidney, adrenal gland, and brain (reviewed in Reference 1). It is now becoming clear that cells expressing renin and angiotensinogen (AGT) are in close proximity to each other and to cells expressing angiotensin type 1 (AT1) receptors in a number of tissues including the brain.2,3 This suggests the potential for local synthesis and action of angiotensin independent of its production in the systemic circulation. In addition, some cells in the brain coexpress both proteins.3 This has led us and others to question whether the RAS can function intracellularly either through the intracellular production or intracellular action of angiotensin II (Ang II). Interestingly, the intracellular action of Ang II was proposed as early as 1971 when Robertson and Khairallah4 reported nuclear localization of the peptide in smooth and cardiac muscle. More recently, Re5 and others6 have described Ang II as part of a class of peptide hormones that act intracellularly, as an “intracrine.”7,8

Circulating Ang II may act intracellularly by binding to AT1 receptors, which are subsequently internalized,7,8 and Ang II–dependent internalization of the AT1 receptor has been reported in neurons.9 This suggests that extracellular Ang II is first internalized after ligation of the AT1 receptor. However, there has been the suggestion that Ang II may be synthesized within the cell and, thus, acts intracellularly. First, it has been reported that renin can be internalized using the mannose-6-phosphate receptor, although some have suggested that this might act simply as a clearance mechanism.10 A receptor for renin and prorenin has also been identified recently.11 Other compelling evidence in support of intracellular production of Ang II comes from studies reported by our laboratory and others that an alternative form of renin mRNA exists in several tissues.12–14 This altered form of the protein lacks the signal peptide (and, thus, is not secreted) and the first 15 amino acids of the prosegment (and is, therefore, constitutively active) suggesting the formation of an intracellular form of active renin. The alternative REN (intracellular form of active renin; icREN) mRNA start site is located 6.2 kb upstream of the classic promoter and encodes a new exon 1 (termed exon 1b) that splices directly to exon 2. This forms a mRNA, which lacks the normal translational initiation
codon in exon I, thus forcing the use of an in-frame ATG present in exon II. Alternative transcripts have been identified for REN in the adrenal gland and heart, as well as in the brain; and biochemical studies suggest that this form of REN is active enzymatically. Increased expression of the icREN was reported in the heart after myocardial infarction. This would support the hypothesis that there may be intracellular formation of Ang II in these different tissues. However, it is unknown whether this form of REN has any physiological relevance. We, therefore, directly tested the hypothesis that intracellular production of a nonsecreted active renin in the brain can participate in the regulation of BP and electrolyte homeostasis.

Methods

Generation of Glial Fibrillary Acidic Protein-icREN Transgenic Mice

The generation of the glial fibrillary acidic protein (GFAP)-secreted prorenin (sREN) and GFAP-icREN constructs, production of transgenic mice, and their genotyping is described in the online supplement to the Methods (available at http://hyper.ahajournals.org). Double-transgenic mice carrying either GFAP-icREN or GFAP-sREN and GFAP-human AGT (hAGT) were generated by breeding heterozygous mice. Nontransgenic age- and sex-matched littermates, double-transgenic mice carrying either GFAP-icREN or GFAP-sREN (S) from GFAP-icREN (IC). 100-bp markers are shown (M).

Figure 1. Schematic map of the GFAP-icREN construct. A schematic map of the transgene is shown. The start site of transcription is indicated as +1. The sREN transgene expresses full-length preprorenin that becomes active by virtue of a mutation that alters the normal prorenin-converting enzyme site to a furin (F) cleavage site. The icREN construct initiates translation at the ATG inside exon II making a truncated prorenin protein lacking a signal peptide. The construct retains the normal prorenin-converting enzyme site to a furin (F) cleavage site. The transgene was excised as a BssHII fragment for microinjection. Insert shows a genotyping assay distinguishing GFAP-sREN (S) from GFAP-icREN (IC), 100-bp markers are shown (M).

Statistical Analysis

BP and daily drinking measurements for individual mice were averaged to obtain each individual number. Data were then ex-

Plasma Renin Assay, Cerebrospinal Fluid Collection, and Western Blot Analysis

Plasma human renin concentration and plasma mouse renin activity (PRA) were determined in single transgenic mice as described previously. Radioimmunoassay was performed on plasma using Ang-I-125I-labeled radioimmunoassay kit (DiaSorin). Samples were diluted with reagent blank to remain on the linear portion of the standard curve. Collection of cerebrospinal fluid (CSF) from the mouse was detailed in the online supplement. The CSF collected from the mouse was pooled together to harvest a sufficient amount of protein. Sample proteins were then separated by electrophoresis on a 10% sodium dodecyl sulfate polyacrylamide gel and transferred to a nitrocellulose membrane. Proteins were detected using an hREN rabbit antiseras (a gift from F. Hoffman LaRoche Pharmaceuticals).

Physiology

Mice were anesthetized with sodium pentobarbital (50 mg/kg) and then were implanted with TA11PA-C20 radiotelemeters (Data Sciences International) in the left carotid artery for direct measurement of arterial pressure (AP) and heart rate (HR) as described previously. Mice were given 7 days to recover, after which time HR and AP were continuously recorded for 1 hour/day for 3 to 4 consecutive days. BP was determined by the average of each individual sampling segment. A catheter was also inserted in the right jugular vein for systemic administration of drugs, and an ICV cannula was inserted for the microinjection of drugs into the lateral ventricles as described in detail previously. All of the experiments were performed in conscious, unrestrained mice in their home cages. ICV or IV infusion studies were performed after at least a 30-minute stabilization period after insertion of the microinjector into the ventricular guide cannula or connection of the venous line to a syringe. AP and HR were measured for 1 hour after infusion of drugs, and each infusion study was performed on different days. Cardiovascular responses to ICV Ang II (typically an increase in 15 to 20 mm Hg) were recorded on the first day of measurement to confirm correct placement of the ICV injector. To additionally confirm the correct placement of the cannula, methylene blue dye (5 µL) was injected after the completion of all of the experiments. The effect of ICV injection of losartan (10 µg, generous gift of Merck Research Laboratories, Rahway, NJ) and artificial CSF (ACSF, in mmol/L: NaCl 136, KCl 5.6, NaHCO3 1.2, NaH2PO3 1.2, MgCl2 1.2, and CaCl2, pH 7.4) on basal AP and HR was examined. The effect of IV injection of losartan (10 µg) was performed as a control. ICV and IV infusions were done over a 30-s period with compounds dissolved in ACSF and saline and delivered in a volume of 0.5 and 10 µL, respectively. All of the hemodynamic data were collected and analyzed on a computer using Dataquest ART and the Telemetry Analyzer (JCL Consultants).

Water intake was measured individually in metabolic cages with standard chow and tap water ad libitum for 3 days. To determine salt preference, mice were fed salt-deficient chow and given 0.3 mol/L hypertonic saline and tap water in separate randomized burettes ad libitum for 3 days. Salt preference was calculated as a percentage by dividing the volume of saline consumed by the total volume of fluid consumed. Urinary volume was measured by collecting 24-hour urine in metabolic cages with standard chow ground with tap water (100 g of chow/150 mL of water) and tap water ad libitum daily for 3 days. Urinary osmolality was measured using a freezing-point osmometer (Fiske 2400 multi-sample). The generation of the glial fibrillary acidic protein (GFAP)-secreted prorenin (sREN) and GFAP-icREN constructs, production of transgenic mice, and their genotyping is described in the online supplement to the Methods (available at http://hyper.ahajournals.org). Double-transgenic mice carrying either GFAP-icREN or GFAP-sREN (S) from GFAP-icREN (IC), 100-bp markers are shown (M).
pressed as mean±SE. All of the comparisons were made with nontransgenic littermates. PRA was compared using Student’s t test, whereas BP and drinking were compared by ANOVA. A value of \( P<0.05 \) was considered statistically significant.

**Results**

Transgenic mice were generated using a human GFAP promoter fused to a cDNA encoding the alternative intracellular form of renin (Figure 1). To do so, we modified the classical hREN cDNA by PCR amplifying a fragment using a 5' primer just distal to the internal ATG present in exon-2 and a 3' primer downstream of the termination codon. Hence, this hREN does not contain any of the renin signal peptide and is missing the first third of the prosegment and, thus, should remain intracellular and be constitutively active as reported previously.13 Interestingly, an analysis of renin protein sequences revealed that the ATG in exon II encoding the initiator methionine of icREN is perfectly conserved in human, mouse, rat, sheep, and dog renin and is also retained in Zebrafish and Fugu renin, suggesting that an important function has been conserved evolutionarily (Figure 2).

Tissue-specific expression of the GFAP-icREN transgene was evaluated using RNase protection (Figure 3A). Although transgene mRNA was present in brain from mice from all 4 transgenic lines (data not shown), ectopic expression in other tissues varied considerably. Expression of icREN in line 19560/3 was almost exclusively localized to the brain with only a low level detected in the lung (Figure 3A). We recognized the importance of sacrificing the level of expression (which was higher in other lines) in favor of a model with brain-specific expression. We next measured plasma hREN concentration in the presence of excess endogenous hAGT to determine whether any ectopic expression of the transgene in tissues outside the brain resulted in a significant increase in hREN in the systemic circulation. We found no significant differences in human plasma renin concentration (which were at the background of the assay) when comparing transgenic with nontransgenic mice (Figure 4). Accordingly, it is unlikely that a significant amount of hREN protein is released into the systemic circulation in this transgenic model. We previously reported the similar absence of circulating hREN in mice expressing the secreted form of renin specifically in glial cells.16 Interestingly, there was a modest increase in endogenous PRA in the GFAP-icREN mice compared with nontransgenic littermates. The mechanism causing this increase remains unclear, especially provided that the measurement of plasma mouse renin was performed in single icREN transgenic mice where the level of systemic and brain Ang II should remain unaltered.

We next felt it was crucial to confirm that renin in GFAP-icREN was not secreted. To accomplish this, we measured hREN in the CSF collected from GFAP-icREN and compared this with CSF from nontransgenic control mice. As an additional control, we also measured CSF renin in transgenic mice expressing secreted renin encoded from the same promoter (GFAP-sREN),16 after first comparing the level of GFAP-icREN and GFAP-sREN mRNA expression in the brain. RNase protection assay revealed equivalent levels of transgene expression in both transgenic lines allowing us to make a direct comparison between the 2 mouse models (Figure 3B). As predicted, hREN, migrating at the same position as purified recombinant hREN, could be detected in the CSF of the GFAP-sREN mice (Figure 5). Conversely, no
specific hREN band was detected in the CSF of either GFAP-icREN or nontransgenic mice. This observation was replicated in separate experiments using independent CSF samples (Figure 5 left and right panels provide examples).

In order to evaluate the physiological consequence of icREN overexpression, we generated 2 double-transgenic mouse models and measured drinking, urine volume, and BP. The intracellular model was generated by cross-breeding GFAP-icREN with mice expressing hAGT from the GFAP promoter (GFAP-hAGT), whereas the secreted model was made by cross-breeding GFAP-sREN with GFAP-hAGT.16,21 The generation of the double-transgenic mice was necessary because of the species specificity of the renin-AGT reaction.22 Double-transgenic mice expressing icREN exhibited a significant increase in drinking volume compared with nontransgenic littermates, although the increase tended to be less than that observed in double-transgenic mice expressing sREN (Figure 6A). On the contrary, there was only a modest increase in urinary volume in the mice expressing icREN, which did not reach statistical significance, whereas a significant increase in urine volume was detected in mice expressing sREN (Figure 6B). There was no significant difference in the urine osmolality or concentration of sodium or potassium when comparing all 3 of the groups (Supplemental Table, available online at http://hyper.ahajournals.org). In addition, there was no significant difference in salt preference when comparing GFAP-icREN/GFAP-hAGT (31.8±10.0%), GFAP-sREN/GFAP-hAGT (35.4±9.4%), and nontransgenic control (31.5±6.7%) mice. As expected, all of the single transgenic mice were phenotypically similar to nontransgenic littermates (data not shown). It is noteworthy that double-transgenic mice expressing either icREN or sREN exhibited a significant increase in mean AP compared with nontransgenic littermates (Figure 7A). Mean AP significantly decreased in both models after ICV injection of losartan (Figure 7B), whereas there was no effect of either ICV ACSF or IV losartan in any group of mice.

**Discussion**

We first became interested in the concept of intracellular Ang II synthesis after we and others identified an alternative form of renin mRNA in the mouse, rat, and human brain.12–14 This alternative mRNA lacks the normal translational initiation codon in exon 1, because the alternative first exon splices directly to exon 2 and, thus, forces the use of an in-frame ATG initiation codon in exon 2, because the alternative first exon splices directly to exon 2 and, thus, forces the use of an in-frame ATG initiation codon present in exon 2. Importantly, this methionine is evolutionarily conserved, further supporting its physiological importance. That it lies in the prosegment of the protein and would normally be cleaved when prorenin is processed to active renin suggests that it may not be required for the enzymatic activity of renin and its conservation and importance lies in its ability to initiate synthesis of intracellular renin. The resultant icREN protein (also called Renin-B by others) lacks the signal peptide in its entirety and also the first 15 amino acids of the prosegment suggesting the formation of an intracellular active renin. Interestingly, in humans, the alternative first exon lies 6.2 kb upstream of the classical transcriptional start site, between enhancer elements active in renal juxtaglomerular cells and choriodendal cells.12,23 In contrast, in mouse and rat, the alternative first exon lies within the first intron.13 Intracellular renin was reported as the exclusive isoform in the rat heart to be induced

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![Figure 4](http://hyper.ahajournals.org/)

**Figure 4.** Plasma renin activity and concentration. Shown is the PRA (■) and plasma human renin concentration (PRC □) as determined by a radioimmunoassay of plasma from GFAP-icREN transgenic mice (n=6) compared with their nontransgenic (NT) littermates (n=9). Expressed as mean±SE. *P<0.05 compared with NT.

![Figure 5](http://hyper.ahajournals.org/)

**Figure 5.** Presence of hREN in the CSF. Western blot analysis detecting hREN in the CSF of GFAP-sREN (sREN), GFAP-icREN (icREN), and nontransgenic (NT) mice using an hREN-specific antibody. Purified human renin was used as a positive control. *Position of the specific hREN band. Left and right blots were derived from independent samples collected on different days.

![Figure 6](http://hyper.ahajournals.org/)

**Figure 6.** Drinking and urinary volume in double-transgenic mice. Shown is the 24-hour drinking volume (A) and urinary volume (B) in GFAP-sREN/GFAP-hAGT (S, ■, n=11), GFAP-icREN/GFAP-hAGT (IC, □, n=9) compared with nontransgenic littermates (NT, △, n=9). Expressed as 3-day mean±SE. *P<0.05 compared with NT.
after myocardial infarction. Interestingly, the first glimpse of a potential role of mitochondrial renin in steroid biosynthesis was suggested, there is no evidence supporting its function in adrenal or in any other tissue at this time.

In order to provide proof-of-principal that this alternative form of renin could play a role in BP and fluid homeostasis, we developed a transgenic mouse model that overexpresses intracellular renin specifically in astrocytes. Cellular specificity was provided by the GFAP promoter. Importantly, whereas a significant amount of human renin could be detected by Western blot in the CSF of mice expressing a secreted form of renin (GFAP-sREN), there was no CSF renin detected in mice expressing the intracellular form (GFAP-icREN). We felt it was necessary to confirm this experimentally, although the icREN lacked a signal peptide. We also confirmed that the sREN and icREN transgenes were being expressed at equivalent levels. This assured us that any differences in phenotypes measured would be because of the differences in secreted versus intracellular renin and not the level of expression of the transgenes.

We observed that the BP increase in mice expressing icREN was similar to the increase in mice expressing sREN. BP in both models was normalized by ICV injection of losartan, whereas the same dose given systemically had no effect. This suggests that the effect observed was because of the local actions of Ang II in the brain, not from leakage of Ang II into the systemic circulation. This, coupled with our biochemical data showing no renin in CSF, suggests that icREN could cleave AGT intracellularly to produce angiotensin I (Ang-I), thus confirming the enzymatic activity of icREN could cleave AGT intracellularly to produce angiotensin II. This, coupled with our biochemical data showing no renin in CSF, suggests that icREN could cleave AGT intracellularly to produce angiotensin II.

Perspectives
To our knowledge, this is the first observation describing a functional role for the alternative form of intracellular active renin in the brain. Consequently, this offers the possibility that an intracellular or intracrine RAS exists in this tissue. Re defines an intracrine as “a peptide hormone or factor that acts in the intracellular space either after internalization or retention in its cell of synthesis.” One implication of this definition is that Ang II has an intracellular function distinct from those caused by activation of cell surface AT1 or AT2 receptors. Intracellular Ang II has been implicated to stimulate the transcription of AGT, renin, platelet-derived growth factor, and the oncogene c-myc in response to binding to nuclear Ang II AT1 receptors. This definition also implies
that extracellular Ang II is either internalized or directly synthesized in the same cell in which it acts. AT$_1$-dependent internalization of Ang II has been reported in a number of cell types, including neurons.\textsuperscript{7–9} Our studies using reporter genes indicate that some cells in the brain may coexpress renin and AGT.\textsuperscript{3} By extension, therefore, our data suggest the possibility that Ang-I, and perhaps Ang II, is formed intracellularly. Although this concept has been suggested previously to occur in the heart,\textsuperscript{29} these are the first data suggesting that it may also occur in the brain. Additional studies will have to be performed to determine the exact mechanisms by which intracrine RAS regulates BP and electrolyte homeostasis and the relative importance of the classical and intracrine pathways. It will be important to determine whether this mechanism exists in neurons, in particular those neurons containing intracellular Ang II that project between nuclei controlling cardiovascular function and use Ang II as a neurotransmitter.

Acknowledgments

This work was supported by National Institutes of Health grants HL48058, HL61446, and HL55006 (to C.D.S.). D. Lavoie was the recipient of an American Heart Association Heartland Affiliate Postdoctoral Fellowship. We gratefully acknowledge the generous research support of the Roy J. Carver Trust. We thank Deborah R. Davis for excellent technical assistance and Dr Eric Lazartigues for advice.

References

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Hypertension. 2006;47:461-466; originally published online January 30, 2006;
doi: 10.1161/01.HYP.0000203308.52919.dc

Hypertension is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0194-911X. Online ISSN: 1524-4563

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