Angiotensin AT$_2$ Receptor Stimulation Causes Neuroprotection in a Conscious Rat Model of Stroke

Claudia A. McCarthy, BBNS(Hons); Antony Vinh, PhD; Jennifer K. Callaway, PhD; Robert E. Widdop, PhD

Background and Purpose—The angiotensin II type 2 receptor (AT$_2$R) is implicated to be neuroprotective in stroke, although this premise has not been directly tested. Therefore, we have examined the neuroprotective effect of AT$_2$R stimulation after intracerebroventricular administration of AT$_2$R agonist CGP42112 in a conscious rat model of stroke.

Methods—Spontaneously hypertensive rats were treated with either CGP42112 (0.1 to 10 ng/kg/min intracerebroventricularly) alone or in combination with the AT$_2$R antagonist PD123319 (36 ng/kg/min intracerebroventricularly) beginning 5 days before stroke induction. A focal reperfusion model of stroke was induced in conscious spontaneously hypertensive rats by administering endothelin-1 to the middle cerebral artery through a surgically implanted cannula. Behavioral tests were used to assess the severity of neurological deficit as a result of the ischemic event. Cortical and striatal infarct volumes were measured 72 hours poststroke.

Results—Blood pressure was unaffected by treatments. CGP42112 dose-dependently reduced cortical infarct volume poststroke, and PD123319 abolished the neuroprotective effect of CGP42112. PD123319 had no effect on infarct volume alone. These results were consistent with the behavioral findings, indicating that CGP42112 reduced motor deficit on the ledged beam test at 72 hours poststroke and immunohistochemical analyses showing that CGP42112 increased neuronal survival and minimized the loss of AT$_2$R expression in the infarcted region.

Conclusion—Based on infarct, behavioral, and immunohistochemical data, these results indicate that centrally administered CGP42112 exhibits a neuroprotective effect, which was independent of blood pressure. Thus, for the first time, we have shown that central AT$_2$R stimulation is neuroprotective in a conscious rat model of stroke.  

Key Words: AT$_2$ receptors, cerebral infarction, cerebral ischemia, neuroprotection, SHR, stroke

Angiotensin II binds to either the angiotensin II type 1 receptor (AT$_1$R), which is responsible for most of the physiological and pathological actions of angiotensin II, or the angiotensin II type 2 receptor (AT$_2$R), which opposes the actions of the AT$_1$R. AT$_1$R antagonists are commonly used in the treatment of hypertension, one of the main risk factors for stroke. Over the past decade, it has become apparent that the beneficial effects of AT$_1$R antagonists may extend beyond the control of blood pressure.

Animal studies have convincingly demonstrated that, even if given during the reperfusion stage of stroke, AT$_1$R antagonists improve cerebral perfusion during an ischemic event, thus reducing neuronal damage possibly by increasing cerebral vascular compliance, resulting in increased cerebrovascular perfusion during stroke. In this context, treatment with an AT$_1$R antagonist per se caused an increase in vascular AT$_1$R in the cerebral circulation. In addition to their beneficial local vasodilator effects, it is known that sartan compounds exhibit antiapoptotic, anti-inflammatory, and antioxidant properties, indicating that blockade of the AT$_1$R may have both vascular-dependent and -independent neuroprotective actions in the setting of stroke. Integral to the neuroprotective role of the AT$_1$R is its role in neuronal regeneration. Several models of nerve injury have elegantly shown that the AT$_2$R has regenerative capabilities associated with restored behavioral function and anatomic innervation after sciatic nerve crush and optical axotomy as well as increased neurite extension in cell culture.

It has been speculated that the increased stimulation of the AT$_1$R may be responsible for some of the therapeutic effects observed during AT$_1$R blockade. In this context, coadministration of an AT$_1$R antagonist negated neuroanatomical and neurological benefit of candesartan or irbesartan in the filament and cerebral artery occlusion stroke models, demonstrating that AT$_2$R activation contributed to the effect of AT$_1$R antagonists. Other indirect evidence that AT$_2$R stimulation is neuroprotective in the setting of stroke is that AT$_1$R-deficient mice have larger infarct volumes and poorer neurological outcome after stroke. Moreover, AT$_1$R antagonists are less effective in AT$_2$R-deficient mice, again...
confirming that AT$_2$R play a pivotal role in the effect of AT$_2$R antagonists.$^{21}$

However, to date, all investigations examining the neuroprotective nature of the AT$_2$R as recently reviewed by Thöne-Reineke et al$^{22}$ have been indirect because they invoke a diminished or reversible sartan effect during genetic or pharmacological AT$_2$R blockade. Therefore, the main aim of the present study was to stimulate directly AT$_2$R because we hypothesized that stimulation of the central AT$_2$R would be neuroprotective in its own right in a conscious rat model of stroke, thus representing a new pharmacological target in stroke.

Materials and Methods

Full details can be found in the supplement material, available online at http://stroke.ahajournals.org.

Surgical Procedures

Male 15- to 16-week-old (270 to 320 g) spontaneously hypertensive rats (SHR) had a 23-gauge stainless steel guide cannula stereotaxically implanted into the piriform cortex 2 mm dorsal to the right middle cerebral artery as previously described.$^{23,24}$ The stereotaxic coordinates were modified for this strain of rat (0.2 mm anterior, −4.7 mm lateral, and −7 mm ventral relative to bregma). An additional 23-gauge intracerebroventricular (ICV) cannula was also stereotaxically implanted into the left lateral ventricle (−0.8 mm anterior, +1.5 mm lateral, and −3.2 mm ventral relative to bregma) for drug administration. These studies were approved by a Monash University Animal Ethics Committee.

Treatments

Rats were randomly allocated to the following treatment groups: 0.1 μg/kg/min CGP42112 (n = 6; gift from Novatis); CGP42112 (1 ng/kg/min)+PDI23319 (36 ng/kg/min; n = 10; gift from Pfizer); PDI23319 (36 ng/kg/min) alone (n = 10), or saline (n = 11). The ICV cannula and osmotic minipump containing these treatments were implanted 5 days before stroke and continued to deliver treatment for 3 days poststroke. Two additional sham groups, with or without CGP42112 1 ng/kg/min, underwent surgery without stroke induction. These sham groups acted as surgical and histological controls, respectively.

Systolic Blood Pressure

Systolic blood pressure (SBP) was measured before the start of ICV treatment and also 72 hours poststroke (Day 14).

Stroke Induction

Stroke was induced in conscious animals by titrating the administration of the vasoconstrictor, ET-1 (Auspep), to cause temporary occlusion of the right middle cerebral artery.$^{23,24}$ ET-1 was infused through a 30-gauge injector protruding 3 mm beyond the end of the previously implanted guide cannula. Stroke was characterized by behavioral indicators$^{24,25}$ modified to be specific for the SHR strain. Typical behaviors that were observed were continuous contralateral or ipsilateral circling behavior; clenching, dragging, or failure to extend the forelimb contralateral to the side of ET-1 infusion; and forepaw shuffling, jaw flexing, or chin rubbing while circling. Each stroke was graded based on these predetermined behavioral changes using a scale of 1 to 4 with 1 being a mild stroke and 4 being a severe stroke. Core body temperature was monitored rectally using a digital thermometer over a 3-hour period. The experimenter was blinded to the treatments. Only rats with a stroke grade of 4, exhibiting at least 7 of the previously mentioned behaviors, were used for the purpose of this investigation, and any animal with a core temperature >40°C after stroke was euthanized.

Assessment of Motor Function

Motor coordination and limb function were assessed using the ledged beam as previously described.$^{26}$ The ledged beam test was conducted before treatment (Day 0), after recovery from cannula implantation (Day 6), immediately before stroke induction (Day 11), 24 hours poststroke induction (Day 12), and 72 hours poststroke induction (Day 14). All values were compared with presurgery; therefore, each rat acted as its own control. The number of total foot steps taken to run the length of the beam was recorded as well as the number of steps taken on the ledge by each foot. The latter number was recorded as a percentage of the total number of footsteps taken and recorded as percentage error.

Quantification of Ischemic Damage

At 72 hours after stroke, rats were reanesthetized and perfused (25 mL/min) with physiologically buffered saline (0.1 mol/L; pH 7.4) through the apex of the heart. Brains were removed, frozen over liquid nitrogen, and stored at −80°C. Coronal cryostat sections (16 μm) were cut at 8 predetermined levels of the forebrain (−3.20 mm to 6.80 mm relative to bregma), slide-mounted, and stored at −80°C. The infarct area and volume were calculated using a method developed by Callaway and colleagues.$^{27}$ The infarct volume was quantified by integrating the area of damage with the distance between each level.$^{28}$

Neuronal Immunohistochemistry

Neuron integrity was assessed using the neuronal marker NeuN. The number of NeuN-positive cells (identified by anti-NeuN IgG antibody) was counted within a 1-mm$^2$ site in the infarcted and noninfarcted region of the ipsilateral hemisphere and 2 matched regions of the contralateral hemisphere.

Localization of Superoxide by Dihydroethidium Staining

Dihydroethidium (2 μmol/L; Invitrogen) was used as previously described$^{29}$ to detect superoxide in frozen coronal cryostat sections (16 μm; −0.8 mm relative to bregma in vehicle).

Angiotensin 2 Receptor Immunohistochemistry

AT$_2$R expression was assessed as previously described by Roulston et al.$^{30}$ Images were taken from the cortical noninfarcted and infarcted regions of the ipsilateral hemisphere and 2 matched regions of the contralateral hemisphere. The number of cells immunopositive for AT$_2$R was counted within a 0.25-mm$^2$ site for each region.

Statistical Analysis

Results are presented as mean±SEM. Ledged beam and blood pressure data were analyzed using 2-way repeated-measures analysis of variance (ANOVA) with individual differences assessed using Bonferroni posttest. Infarct area, AT$_2$R expression, neuronal expression, and superoxide production were assessed using one-way ANOVA with individual differences assessed using Dunnett’s post-test. All statistical analyses were performed using PRISM (GraphPad), and a value of $P<0.05$ was considered statistically significant.

Results

Systolic Blood Pressure

There was no significant difference in SBP between any of the treatment groups, and CGP42112 did not significantly alter SBP (Table).

Infarct Volume

When compared with vehicle (112.60±21.03 mm$^3$), CGP42112 (1 ng and 10 ng/kg/min) significantly reduced cortical infarct volume at 72 hours poststroke (16.43±5.21 and 9.34±5.30 mm$^3$, respectively; $P<0.01$, $P<0.001$ versus vehicle). In addition, CGP42112 (10 ng/kg/min) also reduced...
striatal infarct volume when compared with vehicle (12.40±3.66 and 30.27±4.58 mm³, respectively; P<0.05). While the lowest dose of CGP42112 also reduced cortical damage, this result did not reach statistical significance. This neuroprotective effect observed in the animals receiving CGP42112 (1 ng/kg/min) was reversed by PD123319; however, PD123319 had no effect when administered alone (Figure 1).

**Motor Function**

Stroked rats treated with vehicle showed a significant increase in percentage errors on the ledged beam at 1 and 3 days poststroke indicating that the test is sensitive to stroke-induced deficit. Importantly, there was no change in the percentage errors in the sham-operated, nonstroked animals, confirming that any deficit observed was a stroke-related injury and not due to surgical procedures. CGP42112 (1 and 10 ng/kg/min) significantly reduced errors 1 day poststroke (12±11% and 13±7%, respectively) when compared with vehicle (68±12%; P<0.05 versus vehicle). Furthermore, at 3 days poststroke, all doses of CGP42112 significantly reduced errors (22±16%, 5±3%, and 10±10% for 0.1, 1 and 10 ng/kg/min, respectively) versus vehicle (73±9%; P<0.05 to 0.01). PD123319 negated the improvements in performance observed in CGP42112-treated rats while having no effect when administered alone. There was no change in percentage error in the sham group at any of the times tested (Figure 2).

**Neuronal Expression**

The number of neurons as indicated by NeuN-immunopositive labeling was significantly lower in the cortical infarct region of the ipsilateral hemisphere in vehicle-treated rats after stroke (8.14±4.10 NeuN-positive cells per mm²) when compared with the nonstroked, sham-operated animals (220.00±32.90 NeuN-positive cells per mm²; P<0.05; Figure 3). The loss of neuronal expression in the vehicle-

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<tr>
<th>Treatment</th>
<th>Pretreatment</th>
<th>72 Hours Poststroke</th>
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<tr>
<td></td>
<td>SBP, mm Hg</td>
<td>SBP, mm Hg</td>
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<tr>
<td>Sham (no stroke; n=6)</td>
<td>201±8</td>
<td>205±6</td>
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<tr>
<td>Vehicle (n=6)</td>
<td>194±10</td>
<td>191±9</td>
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<tr>
<td>CGP42112 (0.1 ng/kg/min; n=6)</td>
<td>172±8</td>
<td>187±5</td>
</tr>
<tr>
<td>CGP42112 (1 ng/kg/min; n=9)</td>
<td>171±12</td>
<td>180±10</td>
</tr>
<tr>
<td>PD123319 (36 ng/kg/min; n=10)</td>
<td>197±8</td>
<td>194±6</td>
</tr>
<tr>
<td>CGP42112 (1 ng/kg/min)+</td>
<td>189±5</td>
<td>185±5</td>
</tr>
<tr>
<td>PD123319 (36 ng/kg/min; n=10)</td>
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Figure 1. Infarct area. A–E, Histological sections showing typical infarcted (darker area) and noninfarcted regions from SHR that were either (A) sham-operated nonstroked or treated with (B) vehicle, (C) AT₂R agonist CGP42112 1 ng/kg/min, (D) CGP42112 (CGP) 1 ng/kg/min+PD123319 36 ng/kg/min, or (E) PD123319 alone. Mean data±SEM for infarct volume 72 hours poststroke in (F) cortical and (G) striatal regions on the ipsilateral side are shown for vehicle (n=11); CGP42112 at 0.1 ng/kg/min (n=6), 1 ng/kg/min (n=9), and 10 ng/kg/min (n=6); AT₂R antagonist PD123319 alone (n=10), and in combination with CGP 1 ng/kg/min (n=10). *P<0.05, **P<0.01, ***P<0.001 versus vehicle (one-way ANOVA).
treated group extended to the matched region corresponding to the infarct region on the contralateral hemisphere. Importantly, CGP42112 (1 ng/kg/min) ameliorated the loss of Neun-immunopositive cells (82.75 ± 40.17 NeuN-positive cells per mm²) in the ipsilateral infarcted region. Coadministration of PD123319 with CGP42112 reversed the CGP42112-induced increase in neuronal survival in the ipsilateral hemisphere. PD123319 itself did not alter neuron number compared with vehicle-treated stroke rats.

Superoxide Production

Superoxide production was elevated globally after stroke induction except for in the infarcted region of the ipsilateral hemisphere of the CGP42112 (1 ng/kg/min) -treated group. There was no treatment effect on superoxide production on the contralateral hemisphere or in the noninfarcted region (Figure 4).

AT₂ Receptor Immunohistochemistry

AT₂R expression was lower in the cortical infarct region in the ipsilateral hemisphere of stroked vehicle-treated rats. CGP42112 (1 ng/kg/min) reversed the loss of AT₂R expression in the infarct region (Figure 5). Additionally, CGP42112 tended to increase AT₂R expression in the noninfarced region of the ipsilateral hemisphere as well as in the contralateral hemisphere. In the absence of stroke, CGP42112 treatment had no effect on the number of AT₂R-immunopositive cells (data not shown). There was no significant change in the number of AT₂R-immunopositive cells in the striatal region (data not shown).

Discussion

This investigation is the first study to show directly that stimulation of the AT₂R is neuroprotective against an ischemic stroke. Using a model of stroke in conscious SHRs, we demonstrated that pretreatment with the AT₂R agonist CGP42112, across a nanomolar dose range, almost completely prevented cortical infarction and preserved brain function assessed by neuroanatomical and behavioral measurements, all of which was independent of changes in SBP.

Previous studies have indirectly implicated the beneficial effect of AT₂R stimulation after stroke, since the reduction in infarct volume and neurological deficit observed during AT₂R blockade were reversed with the coadministration of an AT₂R antagonist. Furthermore, when compared with wild-type mice, AT₂R knockout mice have larger infarct areas and poorer neurological outcome after stroke. Thus, to date, all findings regarding the role of the AT₂R have been based on indirect studies inhibiting AT₂R function by pharmacological or genetic means. Moreover, many of the previous studies use models of stroke that induce large infarcts, which are less likely to occur in a clinical setting and/or permanently occlude the middle cerebral artery, which eliminates the potentially damaging reperfusion phase of stroke.

To this end, we examined the role of the AT₂R in a model of stroke that has several advantages over other models. First, rats were hypertensive, an important risk factor for stroke. Second, animals were conscious during the stroke procedure, thus avoiding the influence of anesthesia, which itself can cause neuroprotection. Third, by using a vasoconstrictor such as ET-1, the current model exhibits initial cerebral vasoconstriction, reducing perfusion, followed by a reperfusion phase during ET-1 washout. Moreover, the severity of stroke can be controlled using a predetermined scale of behavioral indicators, which correlates with the degree of neuronal damage in this model.

The current results demonstrated a dose-related neuroprotective effect of CGP42112 that was more striking in the cortex than in the striatum. Consistent with our findings, it was previously reported, using this model, that there was less neuroprotection in the striatal region when compared with the cortical region, because the striatal region is generally considered to be the core of the infarct and refractory to therapeutic intervention.

These results of the current study are remarkable for several reasons. Often, the effects of AT₂R activation need to
be unmasked after \( \text{AT}_{1}\text{R} \) blockade, as is the case of the peripheral vasodilator effects of CGP42112 in conscious SHRs.\(^3\) However, we found that the \( \text{AT}_{2}\text{R} \) agonist alone had a striking effect on infarct volume even in the absence of \( \text{AT}_{1}\text{R} \) blockade and indeed was comparable in its neuroprotective effect to that of an \( \text{AT}_{1}\text{R} \) antagonist in the only study that has centrally administered candesartan, albeit in a different model.\(^1\) Furthermore, the doses of CGP42112 were at least 1000-fold less than what we have previously used for examining vasodilatation after intravenous administration.\(^3\) Such differences point toward increased sensitivity to the functional effects of central \( \text{AT}_{2}\text{R} \) activation. However, we found that the \( \text{AT}_{2}\text{R} \) had no tonic influence, because the \( \text{AT}_{2}\text{R} \) antagonist PD123319 had no effect on stroke outcome when administered alone, although when coadministered with CGP42112, PD123319 negated any neuroprotective effect, thus confirming that CGP42112 was acting via the \( \text{AT}_{2}\text{R} \). Importantly, these effects occurred in the absence of a reduction in SBP, which is well known to be neuroprotective, although it is possible that local cerebral vasodilatation via \( \text{AT}_{2}\text{R} \) stimulation may play a beneficial role.\(^4\)–\(^7\)

Our behavioral data indicated that all 3 doses of CGP42112 reduced motor deficit at 24 hours poststroke, although there was some variation in responses at this time, which may reflect the individual variation often seen in behavioral studies and the relatively small sample size. In any case, this neuroprotective effect was more striking after 72 hours. Moreover, in the current study, the lowest dose of CGP42112 improved motor performance after stroke, whereas the reduction in infarct volume failed to reach statistical significance. \( \text{AT}_{2}\text{R} \) signaling has been associated with many neuron-regenerative processes, including increased dendrite branch-
ing and neurite outgrowth,\textsuperscript{12,15} thus facilitating functional recovery. Importantly, the behavioral improvement mediated by CGP42112 was reversed by the coadministration of an AT\textsubscript{2}R antagonist, again suggesting that the neuroprotection was mediated via AT\textsubscript{2}R. Consistent with this notion, stroke resulted in a complete loss of neurons identified by the neuronal marker NeuN\textsuperscript{12} in the infarcted tissue compared with the sham group, and AT\textsubscript{2}R stimulation significantly increased neuronal survival in a PD123319-sensitive manner. CGP42112 has also been reported to bind to non-angiotensin II sites on inflammatory cells\textsuperscript{34,35}; however, this mechanism is not likely to play a major role in the current study because PD123319 reversed all of the neuroprotective effects of CGP42112 in the current study.

Previous research has shown that AT\textsubscript{2}R are neuronally expressed\textsuperscript{12} and that there is a time-dependant modulation in AT\textsubscript{2}R expression after stroke.\textsuperscript{36} In the present study, the loss of the AT\textsubscript{2}R in the infarct region is also most likely to be a consequence of a loss of neuronal cells in the ischemic area, which has been confirmed by NeuN staining. CGP42112 increases neuronal survival and therefore also preserves AT\textsubscript{2}R expression specifically in the ischemic area. It is interesting to note that some loss of neuronal cells in the vehicle-treated group also extends to the matched region on the contralateral hemisphere. The mechanism through which this occurs is presently unclear; however, previous findings have indicated significant changes in areas remote from the ischemic lesion.\textsuperscript{37,38} CGP42112 did not alter AT\textsubscript{2}R in the absence of stroke, confirming that central AT\textsubscript{2}R changes are most likely secondary to neuronal damage.

Oxidative stress is a major contributing factor to the pathology of stroke. AT\textsubscript{1}R stimulation causes an increase in superoxide production, whereas AT\textsubscript{2}R opposes this effect because AT\textsubscript{2}R-deficient mice had elevated levels of superoxide in the ischemic area after stroke.\textsuperscript{20,39} In the current study, stroke caused a global increase in superoxide production, and this effect was attenuated in the infarct region by CGP42112, ie, in the same area in which AT\textsubscript{2}R expression has been preserved. While the role of the AT\textsubscript{2}R in oxidative stress is still not fully understood, the inverse relationship between superoxide production and AT\textsubscript{2}R expression suggests that the AT\textsubscript{2}R reduces oxidative stress induced during ischemia. In addition, superoxide production was increased on the contralateral noninfarcted hemisphere suggesting that stroke is a

Figure 5. AT\textsubscript{2}R expression. A, Effect of AT\textsubscript{2}R agonist CGP42112 1 ng/kg/min (CGP; n=9) and vehicle (V)-treated SHR (n=7), and sham (S)-operated (n=6) SHR on AT\textsubscript{2}R-immunopositive cells in infarced cortical (open columns) and noninfarced (filled columns) regions on the ipsilateral hemisphere and corresponding regions on the contralateral hemisphere. Mean data±SEM; *P<0.05 versus corresponding region in vehicle-treated group (one-way ANOVA). B–D, Immunohistochemical sections from SHR that were either (B) sham-operated nonstroked or treated with (C) vehicle or (D) AT\textsubscript{2}R agonist CGP42112 1 ng/kg/min depicting AT\textsubscript{2}R immunoreactivity (brown).
global phenomenon. In accordance, using the same model, Miller et al. found that superoxide production was increased in the contralateral cerebral vessels at 24 hours poststroke.

In conclusion, we have directly stimulated AT2R using CGP42112 in a clinically relevant model of stroke and have demonstrated a striking reduction in both cortical and striatal infarct volume. These findings are consistent with markedly improved behavioral outcome induced by the striking reduction in motor deficit at both 24 hours and 72 hours poststroke. We confirmed that CGP42112 was acting through the AT2R by reversing all the neuroprotective changes with the coadministration of PD123319. Neuroprotective mechanisms are likely to involve AT2R-mediated increased neuronal survival in addition to a well-documented AT2R-mediated vasodilator role, leading to preservation of neuronal function and AT2 receptor expression while having a small inhibitory effect on superoxide production. These studies provide proof-of-principle for a role of AT2R stimulation in neuroprotection, although a limitation of the present study was that CGP42112 was given as a pretreatment before stroke induction. Clearly, studies are required in which CGP42112 is given after stroke to more closely mimic the clinical situation. Collectively, these findings highlight the AT2R as a potential therapeutic target in the treatment of stroke, particularly using AT2R agonists.

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Disclosures

None.

References


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