Decreased cGMP Level Contributes to Increased Contraction in Arteries From Hypertensive Rats
Role of Phosphodiesterase 1

Fernanda R. Giachini, Victor V. Lima, Fernando S. Carneiro, Rita C. Tostes, R. Clinton Webb

Abstract—Recent evidence suggests that angiotensin II (Ang II) upregulates phosphodiesterase (PDE) 1A expression. We hypothesized that Ang II augmented PDE1 activation, decreasing the bioavailability of cyclic guanosine 3’5’-monophosphate (cGMP), and contributing to increased vascular contractility. Male Sprague-Dawley rats received mini-osmotic pumps with Ang II (60 ng min⁻¹) or saline for 14 days. Phenylephrine (PE)-induced contractions were increased in aorta (Eₘₐₓ, 168%±8% vs 136%±4%) and small mesenteric arteries (SMA; Eₘₐₓ, 170%±6% vs 143%±3%) from Ang II-infused rats compared to control. PDE1 inhibition with vinpocetine (10 μmol/L) reduced PE-induced contraction in aortas from Ang II rats (Eₘₐₓ, 94%±12%) but not in controls (154%±7%). Vinpocetine decreased the sensitivity to PE in SMA from Ang II rats compared to vehicle (−log of half maximal effective concentration 5.1±0.1 vs 5.9±0.06), but not in controls (6.0±0.03 vs 6.1±0.04). Sildenafil (10 μmol/L), a PDE5 inhibitor, reduced PE-induced maximal contraction similarly in Ang II and control rats. Arteries were contracted with PE (1 μmol/L), and concentration-dependent relaxation to vinpocetine and sildenafil was evaluated. Aortas from Ang II rats displayed increased relaxation to vinpocetine compared to control (Eₘₐₓ, 82%±12% vs 445%±5%). SMA from Ang II rats showed greater sensitivity during vinpocetine-induced relaxation compared to control (−log of half maximal effective concentration 6.1±0.3 vs 5.3±0.1). No differences in sildenafil-induced relaxation were observed. PDE1A and PDE1C expressions in aorta and PDE1A expression in SMA were increased in Ang II rats. cGMP production, which is decreased in arteries from Ang II rats, was restored after PDE1 blockade. We conclude that PDE1 activation reduces cGMP bioavailability in arteries from Ang II, contributing to increased contractile responsiveness. (Hypertension. 2011; 57[part 2]:655-663.)

Key Words: angiotensin II ■ cGMP ■ hypertension ■ vinpocetine
In the presence and absence of vinpocetine (10\(\mu\)mol/L) for 30 minutes) or sildenafil (10\(\mu\)mol/L for 30 minutes) to evaluate vascular contractility. Relaxation–response curves to vinpocetine (PDE1 inhibitor, 1 nmol/L–100 \(\mu\)mol/L), sildenafil (PDE5 inhibitor, 10 \(\mu\)mol/L–100 \(\mu\)mol/L), and 8-Bromo cGMP (membrane-permeable cGMP analog, 100 nmol/L–10 \(\mu\)mol/L) were performed in aortas contracted with PE (1 \(\mu\)mol/L) and in small mesenteric arteries contracted with U46619 (1 \(\mu\)mol/L), a thromboxane \(A_2\) analog. Vinpocetine, a synthetic alkaloid derivative, is one of the most selective PDE1 inhibitors currently available.\(^{15,19}\) In another set of experiments, vascular segments were incubated with Ca\(^{2+}\)-free plus EGTA buffer for 30 minutes, followed by 3 subsequent washes in Ca\(^{2+}\)-free without EGTA and incubation of the vessels in this buffer for 30 minutes in the presence or in the absence of vinpocetine (10 \(\mu\)mol/L for 30 minutes). Arteries were stimulated with PE (aorta, 1 \(\mu\)mol/L; small mesenteric arteries, 10 \(\mu\)mol/L) and concentration–response curves to CaCl\(_2\) (10 \(\mu\)mol/L–100 \(\mu\)mol/L) were performed.

**Materials and Methods**

**Animals and Blood Pressure Measurement**

Ten-week-old male Sprague-Dawley rats (230 to 250 grams; Harlan Laboratories, Indianapolis, IN) maintained on a 12:12-hour light–dark cycle with rat chow and water ad libitum were used in these studies. All procedures were conducted in accordance with the Guide for the Care and Use of Laboratory Animals of the National Institutes of Health and were reviewed and approved by the Institutional Animal Care and Use Committee of the Medical College of Georgia.

Rats were anesthetized with isoflurane via a nose cone for surgical procedures (initially with 5% and then maintained at 2.5% in 100% oxygen). Osmotic mini-pumps (0.5 \(\mu\)L/hr, 14 days; model 2002, Alzet) were implanted subcutaneously. Animals were divided into 2 groups: a control group infused with vehicle only (8.33 \(\mu\)mol/L), followed by acetylcholine (10 \(\mu\)mol/L) and aortic segments were carefully dissected and mounted as rings. The arteries were mounted in an isometric Mulvany-Halpern myograph (model 610; DMT USA) and recorded by a PowerLab 8/30 data acquisition system (ADInstruments). Both dissection and mounting of the vessels were performed in cold (4°C) physiological salt solution containing (mmol): NaCl, 130; NaHCO\(_3\), 14.9; KCl, 4.7; KH\(_2\)PO\(_4\), 1.18; MgSO\(_4\)\(_7\)H\(_2\)O, 1.18; CaCl\(_2\)-2H\(_2\)O, 1.56; EDTA, 0.026; and glucose, 5.5. Second-order branches of mesenteric artery (~2 mm in length with internal diameter ~150–200 \(\mu\)m) and aortic segments were carefully dissected and mounted as rings. The arteries were mounted in an isometric Mulvany-Halpern myograph (model 610; DMT USA) and recorded by a PowerLab 8/30 data acquisition system (ADInstruments). Both dissection and mounting of the vessels were performed in cold (4°C) physiological salt solution. The second-order mesenteric arteries were adjusted to maintain a passive force of 3 mN, and the aortic ring was placed at a passive force of 30 mN. Arteries were equilibrated for 45 minutes in physiological salt solution at 37°C and continuously bubbled with 5% CO\(_2\) and 95% O\(_2\). Endothelium was mechanically removed with rat hair in small mesenteric arteries and with a metallic bar in the aortic rings. Arterial integrity was assessed first by stimulation of vessels with 120 mmol/L KCl. After washing and a new stabilization, the absence of endothelium was assessed by contracting the segments with phenylephrine (PE; 1 \(\mu\)mol/L), followed by acetylcholine (10 \(\mu\)mol/L). The absence of a relaxation response to acetylcholine stimulation was taken as evidence of endothelium removal. Concentration–response curves to PE (1 \(\mu\)mol/L to 100 \(\mu\)mol/L) were performed in the presence and absence of vinpocetine (10 \(\mu\)mol/L for 30 minutes) or sildenafil (10 \(\mu\)mol/L for 30 minutes).
Results

Blood Pressure Data

After 14 days of infusion, Ang II-treated rats displayed increased systolic blood pressure compared to control rats (166±2 vs 130±4 mm Hg, respectively; n=6).

Effects of Chronic Infusion of Ang II on Vascular Contractility

Aortas from Ang II-infused rats displayed increased maximum contraction to PE compared to control values (168±8% vs 136±4%, respectively; n=6; P=0.0017; Figure 1A). No differences were observed in the –log of half maximal effective concentration (pD2) values between hypertensive and control rats (Table 1).

Smaller mesenteric arteries from Ang II-infused rats displayed augmented contraction to PE compared to control values (170%±6% vs 143%±3%, respectively; n=6; P=0.0006; Figure 1B). No differences were observed in the pD2 values between hypertensive and control rats (Table 1).

Effect of PDE1 Inhibition on Vascular Contractility

After vinpocetine incubation (10 μmol/L for 30 minutes), aortas from Ang II-infused rats displayed a reduction in the contractile response to PE (94%±12%; n=6; P<0.0001) when compared to Ang II aortas without PDE1 inhibition (Figure 1A). PE-induced contraction in aortas from control rats were not affected by vinpocetine incubation (154%±7%; Figure 1A). Vinpocetine incubation reduced pD2 values in Ang II rats and control rats compared to their respective vehicle (P<0.0001), indicating that PDE1 inhibition decreases sensitivity to PE-induced contractile response in aorta (Table 1).

In small mesenteric arteries, the PE-induced maximum contraction was reduced by vinpocetine incubation in Ang II (151.7±5.6%; n=6; P=0.0025), but not in control rats (153.3±3.6%; n=6; Figure 1B). The pD2 value was reduced in small mesenteric arteries from Ang II rats (P<0.0001), but not in control rats, when compared to their respective vehicle groups (Table 1). These data indicate that PDE1 inhibition decreases sensitivity to PE in small mesenteric arteries from Ang II rats.

Together, these results suggest that PDE1 contribution to increased contractile response is greater in aorta and small mesenteric arteries from Ang II-infused rats compared to control rats. Presumably, these results indicate a greater reduction in cGMP by PDE1 in blood vessels from Ang II hypertensive rats.

Effect of PDE5 Inhibition on Vascular Contractility

After sildenafil incubation (10 μmol/L for 30 minutes), aortas from both Ang II-infused (88.5±4.3%; n=6; P<0.001) and control rats (79.1±4.5%; n=6; P<0.001) showed reduction in the maximum contractile response to PE compared to their respective groups without incubation (Figure 2A). Additionally, no differences in PE-induced contraction were observed between Ang II and control aortas after sildenafil treatment.

The pD2 values were decreased after sildenafil incubation, both in Ang II rats (P<0.0001) and in control rats (P<0.0001), indicating that PDE5 similarly contributes to PE sensitivity in aortas from both groups (Table 1).

PE-induced maximum contraction was reduced by sildenafil incubation in small mesenteric arteries from Ang II (117%±9.7%; n=6; P=0.0002) and control rats (109%±10.1%; n=6; P=0.0007) compared to their respective groups without incubation (Figure 2B). The pD2 values were reduced in small mesenteric arteries from Ang II rats.

Table 1. pD2 Values for Phenylephrine-Induced Contraction in the Presence or Absence of Vinpocetine and Sildenafil

<table>
<thead>
<tr>
<th>Artery</th>
<th>Control</th>
<th>Angiotensin II</th>
<th>Control</th>
<th>Angiotensin II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aorta</td>
<td>Vehicle</td>
<td>8.4±1</td>
<td>8.5±1</td>
<td>6.1±0.05</td>
</tr>
<tr>
<td></td>
<td>Vinpocetine</td>
<td>6.2±0.1†</td>
<td>6.5±0.2†</td>
<td>6.0±0.03</td>
</tr>
<tr>
<td></td>
<td>Sildenafil</td>
<td>7.0±0.1†</td>
<td>7.1±0.1†</td>
<td>5.3±0.03†</td>
</tr>
</tbody>
</table>

Concentration–response curves to phenylephrine were performed in aorta and small mesenteric arteries from angiotensin II hypertensive and control rats in the absence or in the presence of vinpocetine or sildenafil (10 μmol/L for 30 minutes). Data are mean±SEM (n=6).

*P<0.05 vs respective control group.
†P<0.05 vs respective vehicle group.
and control rats (*P<0.0001), showing that PDE5 similarly contributes to increased sensitivity to PE in small mesenteric arteries in both groups (Table 1). The current results show that PDE5 activation contributes to increased contractile response in arteries from Ang II and control rats.

Effect of PDE1 Inhibition on Ca\(^{2+}\)-Induced Contraction

Aortas from Ang II-infused rats displayed increased maximum contraction to Ca\(^{2+}\) (CaCl\(_2\)) compared to control values (177%±7.4% vs 155%±5.42%, respectively; n=6; *P=0.037). Vinpocetine incubation reduced maximum contraction in aorta from Ang II and control rats (15.6%±3.2% vs 32.3%±7.5%, respectively; n=6) and abolished differences between the groups (Figure 3A).

Small mesenteric arteries from Ang II rats displayed similar contraction to Ca\(^{2+}\) (CaCl\(_2\)) compared to control values (76.6%±6.1% vs 75.6%±3.5%, respectively; n=6). PDE1 inhibition abolished contraction to Ca\(^{2+}\) (CaCl\(_2\)) in both groups (Figure 3B).

Effect of PDE1 Inhibition on Vascular Relaxation

In this set of experiments, concentration–response curves to vinpocetine and sildenafil and PDE1 and PDE5 inhibitors, respectively, were performed in arteries from Ang II and control rats contracted with PE (10 µmol/L, aorta) or U-46619 (10 µmol/L, small mesenteric arteries).

Cumulative concentrations of vinpocetine resulted in greater relaxation response in aortas from Ang II rats compared to control rats (82.3%±6.1% vs 44.5%±5.2%, respectively; n=6; *P<0.0028; Figure 4A). In this case, no differences were observed in pD\(_2\) values between aorta from Ang II and control rats, showing that aorta from both groups display similar sensitivity to vinpocetine (Table 2).

In small mesenteric arteries, no differences in the vinpocetine-induced maximum relaxation response were observed between Ang II (89.9%±3.5%; n=6) and control rats (90.6%±1.5%; n=6; Figure 4A). The pD\(_2\) value was increased in small mesenteric arteries from Ang II rats compared to control rats (*P<0.029), which indicates that small mesenteric arteries from Ang II rats have augmented sensitivity to PDE1 inhibition (on addition of vinpocetine) compared to control rats (Table 2).

Effect of PDE5 Inhibition on Vascular Relaxation

When sildenafil relaxation curves were performed in aortas, no differences in the maximum response were observed in Ang II compared to control rats (75.8%±4.3% vs 71.7%±12.5%, respectively; n=6; Figure 4B). The pD\(_2\) values were similar between Ang II and control rats (Table 2), indicating that aorta from both groups display similar sensitivity to sildenafil.

In small mesenteric arteries, the sildenafil cumulative curve resulted in a similar relaxation response in Ang II
(93.2% ± 2.4%; n = 6) and control (92.6% ± 6.25%; n = 6; Figure 4B) rats. No differences in the pD2 values were found between Ang II (5.2 ± 0.2) and control rats (Table 2), showing that small mesenteric arteries from both groups display similar sensitivity to sildenafil. These results suggest that PDE1 activation plays a role in augmented contractile responsiveness in arteries from Ang II compared to control rats.

**Effect of Soluble Permeable cGMP Analog and cGMP Activator**

When concentration–response curves to 8-Bromo cGMP, a membrane-permeable cGMP analog, were performed in arteries from control or Ang II rats, no significant differences were observed between the groups (Figure 4C). These results indicate that the overall response of the arteries to cGMP is not different between the groups. No differences in the relaxation responses were observed when concentration–response curves to Bay41-2272, a potent cGMP activator, was evaluated in aortas from control or Ang II rats (Figure 4D). However, a smaller relaxation response was observed in small mesenteric arteries from Ang II rats compared to control (93.9% ± 7.3% vs 113% ± 2.9%, respectively; P = 0.027; Figure 4D) when concentration–response curves to Bay41-2272 were performed. These results suggest that guanylyl cyclase is differently activated in small mesenteric arteries, but not aorta, from Ang II rats.

**Vascular Expression of PDE1 and PDE5 Isoforms**

The vascular expression of PDE1 and PDE5 isoforms was accessed by Western blot technique. Aortas from Ang II-infused rats displayed increased expression of PDE1A, PDE1C, and PDE5 isoforms compared to control rats (Figure 5A). Small mesenteric arteries displayed increased expression of PDE1A compared to control rats (Figure 5B).

**Effects of PDE1 Inhibition on Vascular cGMP Production**

Basal cGMP production was decreased in aortas from Ang II rats compared to control (11.3 ± 0.5 vs 20.0 ± 1.4 pmol/mL, respectively; n = 6; P < 0.0001). When aortas were incubated with vinpocetine (10 µmol/L), cGMP production was increased in Ang II (27.5 ± 1.9 pmol/mL; n = 6; P < 0.0001) as in controls (31.1 ± 1.1 pmol/mL; n = 6; P < 0.0001), and differences between the groups were abolished (Figure 6A).

### Table 2. pD2 Values for Cumulative Concentration Response (Relaxation) Curve to Vinpocetine, Sildenafil, 8-Bromo cGMP, and Bay41-2272

<table>
<thead>
<tr>
<th></th>
<th>Aorta</th>
<th>Small Mesenteric Artery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
<td>Angiotensin II</td>
</tr>
<tr>
<td>Vinpocetine</td>
<td>4.8 ± 0.1</td>
<td>4.6 ± 0.2</td>
</tr>
<tr>
<td>Sildenafil</td>
<td>4.3 ± 0.3</td>
<td>3.8 ± 0.6</td>
</tr>
<tr>
<td>8-Bromo cGMP</td>
<td>4.6 ± 0.2</td>
<td>4.6 ± 0.2</td>
</tr>
<tr>
<td>Bay41-2272</td>
<td>5.3 ± 0.008</td>
<td>5.4 ± 0.09</td>
</tr>
</tbody>
</table>

Concentration–response curves to vinpocetine, sildenafil, 8-Bromo cGMP, and Bay41-2272 were performed in aortas contracted with phenylephrine (1 µmol/L) or small mesenteric arteries contracted with U-46619 (1 µmol/L) from angiotensin II hypertensive and control rats. Data are mean ± SEM (n = 6).

*P < 0.05 vs respective control group.
Similar results were observed in small mesenteric arteries whereas those from Ang II rats had reduced cGMP levels compared to controls (17.4 ± 0.6 vs 25.5 ± 0.8 pmol/mL, respectively; n = 6; P < 0.001). Again, the PDE1 inhibitor increased cGMP levels in small mesenteric arteries from both Ang II (29.7 ± 0.9 pmol/mL; n = 6; P < 0.0001) and control rats (26.8 ± 0.9 pmol/mL; n = 6; P < 0.0001), and differences between the groups were abolished after vinpocetine (Figure 6B).

These data show that augmented activation of PDE1 isoforms in arteries from Ang II rats are contributing to decreased cGMP levels. In addition, PDE1 inhibition was able to abolish differences in cGMP levels between the groups.

**Discussion**

Our major findings are that arteries from Ang II hypertensive rats, compared to control rats, display increased PDE1 expression and activation, resulting in augmented PE-induced contractile maximal response, increased sensitivity to PE stimuli, and impaired cGMP levels. Additionally, PDE1 inhibition abolished differences in the contractile responsiveness between the groups and improved cGMP levels. We found that PDE5 is increased in aorta from hypertensive rats. However, PDE5 inhibition decreased contractile response to PE in arteries from Ang II and control rats in a similar fashion. We speculate that PDE1 may represent a new mechanism by which Ang II enhances vasoconstriction via cGMP-dependent pathways.

Ang II is critical for the regulation of vascular tone, blood pressure, and volume homeostasis. High levels of circulating Ang II lead to increased contractile activity of vascular SMC to agonistic stimuli, vascular growth, migration, apoptosis, and extracellular matrix deposition, which are hallmarks for vascular changes observed during hypertension. Ang II is critical for the regulation of vascular tone, blood pressure, and volume homeostasis. High levels of circulating Ang II lead to increased contractile activity of vascular SMC to agonistic stimuli, vascular growth, migration, apoptosis, and extracellular matrix deposition, which are hallmarks for vascular changes observed during hypertension.22,23

cGMP functions as an antagonist of Ang II actions by counteracting the Ang II signaling pathway at different steps.24,25 For example, cGMP has been shown to block Ang II-stimulated Ca2+ mobilization26 and inhibit several protein kinases that are activated by Ang II.14,27

The functional interplay between Ang II and cGMP are determined by the mutual regulation of Ang II and cGMP signaling pathways at different levels, including nitric oxide (NO) production, guanylyl cyclase activation, cGMP-mediated protein kinase G activation and PDE activation.25

NO directly stimulates guanylyl cyclase, which cause to GTP to be converted into cGMP.28 Additionally, Ang II can stimulate endothelial NO synthase (eNOS) expression.29,30 In vivo experiments showed that Ang II infusion decreases NO production, but this is mainly attributable to the fact that endothelial NO synthase is mainly in the uncoupled form, generating superoxide rather than NO.25,31 Hence, Ang II can negatively medium guanylyl cyclase expression31 and enzymatic activity,32 because of superoxide-related33 and peroxynitrite-related34 mechanisms. Moreover, Ang II de-
stimulation. Our data showed that aortas from Ang II rats displayed increased contractile response to Ca^{2+}, suggesting that this may be 1 possible mechanism that explains increased PDE1 activity.

Ang II-stimulated Ca^{2+} signaling is complex and occurs via multiple pathways to elicit an integrated Ca^{2+} signal. It is well-described that Ang II mediates augmented Ca^{2+} signaling in vascular SMC, primarily by IP3-induced mobilization of intracellular Ca^{2+} and secondarily by increasing Ca^{2+} entry. Considering that PDE1 activation depends on Ca^{2+}, it seems plausible that arteries from Ang II rats may display increased PDE1 activity. It was observed that nitrate relaxation, which is mediated by NO/cGMP, is a process that can be desensitized, leading to nitrate tolerance. This occurs by augmented expression of PDE1A associated with Ca^{2+} supersensitized cells.

Additionally, we showed that PDE1-specific inhibition was able to increase cGMP levels and to abolish the augmented contractile activity difference between arteries from hypertensive and normotensive rats. These are exciting data if we consider a previous report in which vinpocetine, a PDE1 inhibitor, in the presence of inhaled NO was able to enhance pulmonary vasodilation and transpulmonary cGMP without generating a systemic vasodilation. Additionally, 8-methoxyethyl-3-isobutyl-1-methylxanthine, another PDE1 inhibitor, further reduced systemic arterial pressure induced by iloprost, a long-acting prostacyclin analog. Therefore, a combination of current therapies with PDE1 inhibition may be useful. Most recently, it was shown that vinpocetine is able to inhibit inflammation induced by tumor necrosis factor-α by PDE-independent mechanisms. Given the importance of tumor necrosis factor-α in Ang II-induced inflammatory pathways, it seems interesting that a drug that acutely restores vascular contraction during Ang II-induced hypertension may play additional roles in vascular function. For that purpose, chronic studies using PDE1 inhibitors, such as vinpocetine, should be addressed.

It has been shown that SMC mainly express 3 PDE isoforms, including PDE1 and PDE5. Our data show that Ang II increased PDE1A expression in both aorta and small mesenteric arteries, whereas PDE1C was only increased in aorta. PDE1C isoform is closely related to vascular remodeling and proliferation of human vascular SMC, and it was suggested that this enzyme could be a target for treatment of atherosclerosis or restenosis after angioplasty. However, whether Ang II exclusively regulates human SMC proliferations is still unclear. Of importance, differential subcellular localization of the PDE isoforms may account for differential cGMP regulation. Taking this into consideration, this new concept predicts that PDE acts as cyclic nucleotide diffusion barriers through their spatially confined zones of enzymatic activity, contributing to the subcellular compartmentalization of distinct signaling cascades. In this regard, data from our laboratory propose that soluble guanylyl cyclase is compartmentalized in the caveolae and in the cavernosal endothelium, and its spatial organization facilitates NO actions.

In conclusion, we propose that increased PDE1 expression and its activation, as a result of chronic Ang II infusion,
contribute to impaired cGMP levels, resulting in increased vascular response and sensitivity to contractile stimuli.

Perspectives

Regardless of the fact that there is a variety of pharmacological preparations available for therapy, a large number of hypertensive patients are refractory to these treatments. Therefore, new strategies to find new targets to treat hypertensive disease should be encouraged. Considering that PDE1 inhibition resulted in reduction of the maximum contraction response occurred in arteries from Ang II hypertensive rats, it seems that this may be an interesting target to improve vascular functionality in hypertensive subjects. Therefore, we aim to investigate how long-term PDE1 inhibition may change during hypertension. In addition, we would like to see whether PDE1 activation can interfere with other signaling pathways that are modified in hypertension, such as mitogen-activated protein kinase activation.

Sources of Funding

This study was supported by grants from National Institutes of Health (NIH HL71138 and DK83685).

Disclosure

None.

References


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Hypertension. 2011;57:655-663; originally published online January 31, 2011; doi: 10.1161/HYPERTENSIONAHA.110.164327
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

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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