Angiotensin-Converting Enzyme Inhibition Increases Human Vascular Tissue-Type Plasminogen Activator Release Through Endogenous Bradykinin

Mias Pretorius, MBChB, DA (SA); David Rosenbaum, MD; Douglas E. Vaughan, MD; Nancy J. Brown, MD

Background—Angiotensin-converting enzyme (ACE) inhibition potentiates the tissue-type plasminogen activator (t-PA) response to exogenous bradykinin. This study tested the hypothesis that ACE inhibition increases endothelial t-PA release through endogenous bradykinin.

Methods and Results—We measured the effect of intra-arterial enalaprilat (5 μg/min) on forearm blood flow (FBF) and net t-PA release before and during intra-arterial infusion of bradykinin (25 to 400 ng/min) and methacholine (3.2 to 12.8 μg/min) in 24 smokers pretreated with bradykinin receptor antagonist HOE 140 (100 μg/kg intravenously) or vehicle. There was no specific effect of HOE 140 on FBF or forearm vascular resistance (FVR, 29.9±3.6 versus 29.7±3.6 mm Hg · mL⁻¹ · min⁻¹ · 100 mL⁻¹ after vehicle and HOE 140, respectively, P=0.956 between groups). Resting FVR decreased during enalaprilat compared with vehicle or HOE 140, but not compared with baseline, and the effect was similar in the 2 groups (22.0±2.7 and 24.1±2.9 mm Hg · mL⁻¹ · min⁻¹ · 100 mL⁻¹, respectively, P=0.610). In contrast, enalaprilat significantly increased resting net t-PA release (from 0.6±0.4 to 1.7±0.6 ng · min⁻¹ · 100 mL⁻¹, P=0.002); this effect was abolished by HOE 140 (0.1±0.3 ng · min⁻¹ · 100 mL⁻¹, P=0.036 versus enalaprilat alone). Enalaprilat increased the effect of exogenous bradykinin on FBF 60% (from 17.5±2.5 to 28.1±4.0 mL · min⁻¹ · 100 mL⁻¹ during 100 ng/min bradykinin, P=0.001) and on t-PA release 14-fold (from 21.2±3.9 to 317.4±118.9 ng · min⁻¹ · 100 mL⁻¹, P=0.024). Enalaprilat increased the t-PA response to bradykinin to a greater extent than the FBF response, shifting the relationship between net t-PA release and FBF (P=0.005). HOE 140 blocked these effects. There was no effect of enalaprilat or HOE 140 on the FBF or t-PA response to methacholine.

Conclusion—ACE inhibition increases constitutive endothelial t-PA release through endogenous bradykinin. (Circulation. 2003;107:579-585.)

Key Words: angiotensin  ■  bradykinin  ■  fibrinolysis
Methods

Subjects
Twenty-four smokers were studied. Subjects were defined as smokers if they smoked 5 to 25 cigarettes per day. We have previously determined that bradykinin-stimulated t-PA release but not vasodilation is attenuated in otherwise healthy smokers compared with nonsmokers.\(^\text{15}\) After written informed consent was obtained, all subjects underwent a complete history and physical examination. Subjects with cardiovascular, renal, pulmonary, endocrine, or hemato logically, disease were excluded. All subjects were within 30% of ideal body weight. Pregnancy was excluded in women of childbearing potential by measurement of urine \(\beta\)-human chorionic gonadotropin. Subjects with fasting cholesterol \(>5.17 \text{ mmol/L} (200 \text{ mg/dL})\) were excluded.

Experimental Protocol
The study protocol (Figure 1) was approved by the Vanderbilt University Institutional Review Board and conducted according to the Declaration of Helsinki. Subjects were studied in the supine position after overnight fast. An intravenous catheter was placed in the antecubital vein in both arms. After subdermal administration of 1% lidocaine, an 18 gauge polyurethane catheter (Cook Inc) was inserted into the brachial artery of the nondominant arm. Catheter patency was maintained by infusion of 1 mL/min 5% dextrose in water. After catheter placement, subjects rested 30 minutes before baseline measurements. After measurement of basal forearm blood flow (FBF) and blood sampling, graded doses of sodium nitroprusside (SNP), methacholine (MCh), and BK were infused in random order. SNP was infused at 1.6, 3.2, and 6.4 \(\mu\)g/min; MCh at 3.2, 6.4, and 12.8 \(\mu\)g/min; and BK at 100, 200, and 400 ng/min. BK, at these doses, causes vasodilation in part through a nitric oxide synthase (NOS)–dependent pathway.\(^\text{11}\) In contrast, Rongen et al reported that MCh induces vasodilation through a NOS-independent pathway.\(^\text{16}\) Similarly, in a pilot study in 6 subjects, we found no effect of the NOS inhibitor \(N^\text{G}\)-monomethyl-L-arginine (L-NMMA, 4 \(\mu\)mol/min) on MCh-mediated vasodilation (maximal FBF response to MCh 28.0 ± 3.8 mL ⋅ min \(^{-1} ⋅ 100 \text{ mL}^{-1}\) versus 26.8 ± 4.5 mL ⋅ min \(^{-1} ⋅ 100 \text{ mL}^{-1}\) in the absence and presence of L-NMMA). Nevertheless, we chose MCh as the endothelium-dependent\(^\text{17}\) control because it has been shown to stimulate t-PA release.\(^\text{18}\) Each dose of agonist was infused for 5 minutes and FBF was measured during the last 2 minutes.

Thirty minutes after administration of these three drugs, baseline measurements were repeated and subjects were randomized to receive vehicle (normal saline) or 100 \(\mu\)g/kg HOE 140 intravenously over 1 hour. This dose of HOE 140 has no effect on systemic blood pressure or heart rate, but blocks both the vasodilator and t-PA responses to infused BK for at least 3 hours.\(^\text{11,19}\) FBF measurements and arterial and venous sampling were repeated after HOE 140. At this time, enalaprilat was infused in the brachial artery at a rate of 5 \(\mu\)g/min. This dose blocks conversion of Ang I to Ang II and potentiates the vasodilator effect of BK in the forearm.\(^\text{20}\) During enalaprilat, baseline measurements and infusions of MCh and BK were repeated. Three subjects complained of headache during MCh infusion. Two of the first 9 subjects developed transient arm swelling after infusion of BK in the presence of enalaprilat; therefore the dose of BK infused during enalaprilat was reduced to 25, 50, and 100 ng/min in the remaining 15 (7 vehicle-treated, 8 HOE 140-treated) subjects.

Forearm Perfusion Measurements, Blood Sampling, and Biochemical Assays
FBF was measured by strain-gauge plethysmography, as described previously.\(^\text{15}\) After measurement of FBF, simultaneous arterial and venous samples were obtained from the infused arm before and after each dose of MCh and BK. Because SNP does not increase net t-PA release,\(^\text{11,12}\) no blood was drawn during SNP. Infusions were interrupted during arterial sampling.

Blood samples were collected on ice, centrifuged immediately, and plasma was stored at \(-70°C\) until assay. Blood for measurement of PAI-1 and t-PA was collected in tubes containing 0.105 mol/L acidified sodium citrate, and antigen levels were determined with a 2-site ELISA (Biopool AB). t-PA activity was not measured, as we have demonstrated previously that active t-PA increases with t-PA antigen during BK infusion.

Arteriovenous concentration gradients were calculated by subtracting the plasma level measured in simultaneously collected venous and arterial blood. Forearm plasma flow was calculated from the FBF and arterial hematocrit corrected for 1% trapped plasma.

![Figure 1](http://circ.ahajournals.org/) Study protocol. The inset demonstrates the effects of the pharmacological agents studied on the pathways involved in endothelium-dependent vasodilation and t-PA release. PLC indicates phospholipase C; IP<sub>3</sub>, inositol(1,4,5)triphosphate; PLA<sub>2</sub>, phospholipase A<sub>2</sub>; NOS, nitric oxide synthase; PG<sub>I</sub>2, prostacyclin; EDHF, endothelium-derived hyperpolarizing factor; SNP, sodium nitroprusside; MCh, methacholine; and BK, bradykinin.
Thus, individual net release or uptake rates at each time point were calculated by the following formula: net release=\((C_v-C_A) \times \{\text{FFB} \times \{101-\text{hematocrit}/100\}\}\), in which \(C_v\) and \(C_A\) represent the concentration of t-PA in the brachial artery and vein, respectively.

**Statistical Analysis**

Data are presented as mean±SEM. Categorical data were compared with \(\chi^2\) or Fischer’s exact tests, as appropriate. The effect of drugs were compared with a general linear model-repeated measures analysis of variance (ANOVA) in which the between-subject variables were treatment group (vehicle or HOE 140), sex, and ethnicity, and the within-subjects variables were the dose of BK or MCh and the presence or absence of enalaprilat. Although safety considerations required us to reduce the BK dose administered during enalaprilat, all subjects received the 100-ng/min dose in both the presence and absence of enalaprilat; therefore, the effect of enalaprilat on the FBF or t-PA response to this dose was determined with a paired \(t\) test. A 2-tailed probability value \(\leq 0.05\) was considered statistically significant. All analyses were performed with the statistical package SPSS for Windows (Version 11.0.0, SPSS, Chicago).

**Results**

**Subject Characteristics**

Table 1 provides the characteristics of the subjects randomized to vehicle and HOE 140. There were no significant differences between groups in age, sex, race, body mass index, mean arterial pressure (MAP), heart rate, cholesterol, baseline FBF, or baseline net t-PA release. All of the women studied were premenopausal or taking hormone replacement therapy.

**Effect of HOE 140 and Enalaprilat on Resting FBF and Net t-PA Release**

There was no effect of vehicle or HOE 140 on MAP (Table 2). MAP decreased during intra-arterial infusion of enalaprilat in the vehicle-treated group (\(P=0.026\)) but not in the HOE 140-treated group (\(P=0.422\)). Resting FVR increased after infusion of either vehicle or HOE 140 (\(P<0.05\) versus baseline for either treatment, Figure 2 and Table 2). However, FVR remained similar in the vehicle- and HOE 140- treated groups (\(P=0.956\) between groups), suggesting an effect of time or vehicle, rather than a specific effect of BK receptor antagonism on FVR.Resting FVR decreased after intra-arterial infusion of enalaprilat (Figure 2 and Table 2); again the effect was similar in the vehicle- and HOE 140- treated groups (\(P=0.610\)).

**Effect of HOE 140 and Enalaprilat on FBF Response to BK and MCh**

There was no effect of intra-arterial infusion of BK alone (\(P=0.878\)) or in the presence of enalaprilat (\(P=0.796\) on MAP. BK significantly increased FBF in a dose-dependent fashion (\(P<0.001\) Figures 3A and B). Administration of enalaprilat significantly increased the FBF response to BK (\(P=0.024\) in the vehicle-treated group. Hence, the FBF in response to 100 ng/min BK was 60% higher during enalaprilat (\(28.1±4.0\, \text{mL} \cdot \text{min}^{-1} \cdot 100\, \text{mL}^{-1} \) versus \(17.5±2.5\, \text{mL} \cdot \text{min}^{-1} \cdot 100\, \text{mL}^{-1}\), \(P=0.001\)). Pretreatment with the BK receptor antagonist HOE 140 not only blocked the effect of enalaprilat, but also decreased the FBF response to BK to less than that measured in the absence of enalaprilat (\(8.9±1.5\, \text{mL} \cdot \text{min}^{-1} \cdot 100\, \text{mL}^{-1}\) during enalaprilat plus HOE 140 versus \(17.6±2.0\, \text{mL} \cdot \text{min}^{-1} \cdot 100\, \text{mL}^{-1}\) in response to 100 ng/min BK alone, \(P=0.001\)).

There was no effect of MCh alone (\(P=0.512\)) or in the presence of enalaprilat (\(P=0.519\) in the vehicle-treated group) on MAP. MCh significantly increased FBF in a dose-dependent manner, from \(4.4±0.5\) to \(36.1±2.5\, \text{mL} \cdot \text{min}^{-1} \cdot 100\, \text{mL}^{-1}\) (\(P<0.001\)). Enalaprilat (\(P=0.112\) and

**Table 1. Subject Characteristics**

<table>
<thead>
<tr>
<th>Race, white:black</th>
<th>Vehicle</th>
<th>HOE 140</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>33.4±3.2</td>
<td>35.6±2.4</td>
</tr>
<tr>
<td>Body mass index, kg/m²</td>
<td>23.8±1.1</td>
<td>25.7±1.3</td>
</tr>
<tr>
<td>Heart rate, bpm</td>
<td>77.3±3.3</td>
<td>75.3±4.0</td>
</tr>
<tr>
<td>MAP, mm Hg</td>
<td>81.6±2.1</td>
<td>83.6±1.9</td>
</tr>
<tr>
<td>Cholesterol, mg/dL</td>
<td>176.3±7.6</td>
<td>185.7±6.1</td>
</tr>
</tbody>
</table>

**Table 2. Effect of Treatment on MAP, Resting FVR, and Net t-PA Antigen Release**

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>After</th>
<th>Plus Enalaprilat</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAP, mm Hg</td>
<td>78.4±1.9</td>
<td>80.4±2.6</td>
<td>78.3±2.6†</td>
</tr>
<tr>
<td>HOE 140</td>
<td>81.3±2.3</td>
<td>81.7±3.1</td>
<td>80.4±2.9</td>
</tr>
<tr>
<td>FVR, mm Hg · mL⁻¹ · min⁻¹ · 100 mL⁻¹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle</td>
<td>23.0±2.8</td>
<td>29.9±3.6*</td>
<td>22.0±2.7§</td>
</tr>
<tr>
<td>HOE 140</td>
<td>19.6±1.8</td>
<td>29.7±3.6*</td>
<td>24.1±2.9†</td>
</tr>
<tr>
<td>Net t-PA release (ng · min⁻¹ · 100 mL⁻¹)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle</td>
<td>0.4±0.4</td>
<td>0.6±0.4</td>
<td>1.7±0.6‡</td>
</tr>
<tr>
<td>HOE 140</td>
<td>0.4±0.4</td>
<td>0.5±0.7</td>
<td>0.1±0.3</td>
</tr>
</tbody>
</table>

*\(P<0.05\) vs baseline.
†\(P<0.05\), ‡\(P<0.01\), §\(P<0.001\) vs post-vehicle or HOE 140.
\(|P|<0.05\) vs enalaprilat plus vehicle.
HOE 140 \((P=0.763)\) did not alter the FBF response to MCh. The FBF response to MCh was significantly greater than the FBF response to BK in the presence \((P=0.014)\) of ACE inhibition. SNP also increased FBF, from \(4.3 \pm 0.3\) to \(21.6 \pm 1.9\) mL \(\cdot\) min\(^{-1}\) \(\cdot\) 100 mL\(^{-1}\) \((P<0.001)\).

**Effect of HOE 140 and Enalaprilat on Net t-PA Response to BK and MCh**

BK significantly increased net t-PA release from \(0.5 \pm 0.4\) to \(37.8 \pm 9.4\) ng \(\cdot\) min\(^{-1}\) \(\cdot\) 100 mL\(^{-1}\) at the highest dose \((P=0.005,\) Figures 3C and D). Administration of enalaprilat significantly increased the t-PA response to BK \((P=0.001)\) in the vehicle-treated group and there was no interactive effect with sex. Thus, net t-PA release in response to 100 ng/min BK was 14-fold higher during enalapril \((317.4 \pm 118.9\) versus \(21.2 \pm 7.9\) ng \(\cdot\) min\(^{-1}\) \(\cdot\) 100 mL\(^{-1}\), \(P=0.024\)). HOE 140 blocked this effect of ACE inhibition \((P<0.001\) for an ACEI \(\times\) HOE 140 interaction), such that the t-PA response to BK in the presence of enalaprilat plus HOE 140 was similar to that in the absence of enalaprilat \((P=0.422)\). In the 12 subjects who were randomized to vehicle, ACE inhibition shifted the relation-
The disparity may relate to the comparative reported lack of effect of acetylcholine on endothelial t-PA release, as well as FBF. Over the doses given, MCh caused greater vasodilation and less t-PA release than did BK. The effect of MCh on endothelial t-PA release contrasts with a reported lack of effect of acetylcholine on endothelial t-PA release.13,24 The disparity may relate to the comparative decreased potency of acetylcholine and its susceptibility to cholinesterases.25

Importantly, whereas enalaprilat potentiated the vasodilator response to BK, there was no effect of ACE inhibition on MCh-stimulated vasodilation. This contrasts data from Nakamura et al26 indicating that enalaprilat potentiates nitric oxide-mediated endothelium-dependent vasodilation in response to ACh. One explanation for the lack of effect of enalaprilat on MCh-mediated vasodilation is that MCh, unlike ACh, causes vasodilation through a NOS-independent pathway.16 ACE inhibition also potentiated the t-PA response to BK but not that to MCh in this study. Similarly, Labinjoh et al have reported that ACE inhibition enhances the t-PA response to exogenous BK but not to substance P.27 Taken together with the finding that HOE 140 abolished the effect of ACE inhibition on BK-stimulated t-PA release, the data suggest that ACE inhibition enhances vascular t-PA secretion through a BK B2-receptor-specific pathway.

In this study, ACE inhibition enhanced endothelial fibrinolytic function to a greater extent than vasodilator function. For example, enalaprilat increased t-PA release via endogenous BK, even when given at a concentration that did not affect resting FBF. ACE inhibition potentiated the t-PA response to exogenous BK to a greater extent than the vasodilator effect (14-fold versus 60% at the 100-ng/min dose). Conversely, BK receptor antagonism reduced the vasodilator response to BK to a greater extent than the t-PA response.

The mechanism(s) whereby ACE inhibition differentially affected the vasodilator and fibrinolytic functions of the endothelium is not certain. ACE inhibitors potentiate the effects of BK not only by decreasing its degradation but also by enhancing sensitivity to BK at a receptor level.27 In addition, BK may stimulate vasodilation and t-PA release through multiple or different mechanisms. For instance, administration of the NOS inhibitor L-NMMA attenuates the forearm vasodilator response to BK, indicating that the NO contributes to BK-induced vasodilation,11,28 In contrast, L-NMMA alone or in combination with indomethacin does not affect the t-PA response to BK,11 suggesting that t-PA release is mediated through a NOS- and cyclooxygenase-independent pathway. In the present study, the finding that ACE inhibition altered the relationship between BK-stimulated FBF and t-PA release suggests the possibility that ACE inhibition potentiated t-PA release not only by decreasing BK degradation, but also by altering sensitivity to BK at a receptor or post-receptor level.

ACE inhibitors improve fibrinolytic balance in part by decreasing circulating concentrations of PAI-1.3,7 In the present study, although enalaprilat increased constitutive and BK-stimulated t-PA release there was no effect of intra-arterial enalaprilat or BK on net PAI-1 extraction. This relates to the fact that whereas endogenous and exogenous BK stimulate acute release of preformed t-PA from the vasculature,29 ACE inhibition decreases PAI-1 concentrations by preventing the effect of Ang II on PAI-1 expression,30 an effect that would not be seen over the short course of ACE inhibition in the present study. Indeed, Oshima et al have reported that
ACE inhibition reduces circulating PAI-1 concentrations ≥48 hours after initiation of treatment.7

Although this study explored the effect of ACE inhibition on endothelial fibrinolytic function of the forearm vasculature, Minai et al have demonstrated that exogenous BK stimulates t-PA release from the coronary vasculature as well and that this effect is potentiated by ACE inhibition.13 In contrast to the present study, these investigators reported no effect of oral administration of enalapril on resting coronary t-PA release. Similarly, Labinjoh et al did not note an effect of oral quinapril on estimated net t-PA release.12 However, neither group explored the contribution of endogenous BK using HOE 140. Although the discrepancy between the data of Minai et al13 and the results of the present study about the effect of ACE inhibition on resting t-PA release raises the possibility that results obtained in the forearm vasculature may not be applicable to the coronary vasculature, other methodological differences should be considered. For example, intra-arterial infusion of enalaprilat in the present study may have resulted in greater local vascular ACE inhibition than could have been achieved after oral ACE inhibition in either the study by Minai et al13 or that of Labinjoh et al.12 Additional studies are needed to determine whether the effect of ACE inhibition on constitutive endothelial t-PA release is either dose-dependent or vascular bed-specific.

A more important methodological difference between this study and prior studies relates to the inclusion of women. Minai et al studied an older, predominantly (72%) male population and Labinjoh et al studied males exclusively.12,13 An unexpected finding in this study was that ACE inhibition significantly increased net t-PA release only in the female subjects studied. The mechanism for this effect is not certain, but women appear to be more sensitive than men to other effects of ACE inhibitors that are potentially mediated by BK, including cough and angioedema.31 In the present study, all of the women studied were premenopausal or taking hormone replacement therapy. Estrogen has been shown to decrease ACE activity.32 In addition, estrogen upregulates BK receptors,33 activates potassium channels34 (which may in turn promote endothelium-dependent hyperpolarization), and sensitizes human coronary arteries to BK-mediated vasodilation.35 Although the present study was not powered to address sex differences in response to ACE inhibition, per se, and although we cannot exclude the possibility that an effect of ACE inhibition on constitutive t-PA release would have been seen in a larger group of men, studies are needed to further investigate the extent to which sex or estrogen modulate the effect of ACE inhibition on endothelial fibrinolytic function. The clinical relevance of these studies is underscored by recent data from the HOPE trial suggesting a favorable interactive effect of hormone replacement therapy and ACE inhibition on the risk of cardiovascular events.36

In summary, this study demonstrates that ACE inhibition increases constitutive endothelial t-PA release through endogenous BK. This effect appears to be sex specific. In addition, ACE inhibition potentiates the effect of BK on the fibrinolytic function of the endothelium to a greater extent than the vasodilator function. The enhancement of local vascular endothelial t-PA release may contribute to the cardioprotective effects of ACE inhibitors.

**Acknowledgments**

We are grateful to Tami Neal, RN, from Vanderbilt University, Nashville, Tenn, for her nursing assistance and to Dr Ru Jiao Shan (Vanderbilt) for her technical assistance. This work was funded by National Institutes of Health grants HL65193, HL60906, HL007411, RR00095.

**References**


Angiotensin-Converting Enzyme Inhibition Increases Human Vascular Tissue-Type Plasminogen Activator Release Through Endogenous Bradykinin
Mias Pretorius, David Rosenbaum, Douglas E. Vaughan and Nancy J. Brown

Circulation. 2003;107:579-585; originally published online January 27, 2003;
doi: 10.1161/01.CIR.0000046268.59922.A4
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2003 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/107/4/579

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/