Cycloxygenase Inhibition Restores Nitric Oxide Activity in Essential Hypertension

Stefano Taddei, Agostino Virdis, Lorenzo Ghiadoni, Armando Magagna, Antonio Salvetti

Abstract To evaluate whether cyclooxygenase constrictr substances can impair nitric oxide–mediated vasodilation in essential hypertension, in seven normotensive subjects (43 ± 2.1 years, BP, 117 ± 6/81 ± 2 mm Hg) and seven essential hypertensive patients (47 ± 5.2 years, BP, 141 ± 8/98 ± 4 mm Hg), we studied forearm blood flow (strain-gauge plethysmography) modifications induced by metabrahical acetylcholine (0.15, 0.45, 1.5, 4.5, 15 μg 100 mL⁻¹ min⁻¹) in basal conditions, during infusion of N⁰-monomethyl-L-arginine (L-NMMA, 100 μg 100 mL⁻¹ min⁻¹), a nitric oxide synthase inhibitor, or indomethacin (50 μg 100 mL⁻¹ min⁻¹), a cyclooxygenase inhibitor, or simultaneous indomethacin and L-NMMA. In normotensive subjects, vasodilation to acetylcholine (maximum flow increase 445 ± 33%) was unchanged by L-NMMA and this effect was unchanged by indomethacin. In contrast, in hypertensive patients, vasodilation to acetylcholine (maximum flow increase 804 ± 56%, P < 0.01) was unchanged by L-NMMA and this effect was unchanged by indomethacin. Moreover, indomethacin restored the facilitatory effect of L-arginine versus indomethacin alone. Therefore, cyclooxygenase inhibition restores nitric oxide–mediated vasodilation in essential hypertension, suggesting that cyclooxygenase-dependent substances can impair nitric oxide production.

Key Words • hypertension • endothelium • nitric oxide • endothelium-derived factors • indomethacin

Endothelium plays a major role in the modulation of vascular tone through the production and release of different relaxing and constricting factors acting on the underlying smooth muscle cells. The major endothelium-derived relaxing factor is NO, a labile substance derived from L-arginine by the activity of the enzyme NO synthase. Importantly, this process can be competitively inhibited by L-arginine analogues such as L-NMMA. Moreover, EDCF are mainly cyclooxygenase-dependent prostaglandins (thromboxane A₂ and prostaglandin H₂) or superoxide anions.

The crucial role of endothelial cells in vascular homeostasis is further emphasized by the evidence of impaired endothelial-dependent responses in cardiovascular disease such as essential hypertension. Thus, in essential hypertensive patients, vasodilation to endothelium-dependent agonists (mainly acetylcholine or bradykinin) is reduced compared with normotensive control subjects. This abnormality is caused by a defect in NO activity since both L-arginine and L-NMMA, which in normal conditions can increase or reduce the response to acetylcholine, respectively, are ineffective in hypertensive patients. Moreover, indomethacin, a cyclooxygenase inhibitor, can potentiate the vasodilation to acetylcholine in hypertensive patients but not in normotensive control subjects, indicating the synthesis of cyclooxygenase-dependent EDCF. Thus taken together these observations suggest that in essential hypertension endothelial dysfunction is caused by the simultaneous presence of a defect in the L-arginine–NO pathway and production of cyclooxygenase-dependent EDCF.

However, the possibility exists that these alterations are not abnormalities which are parallelly associated with hypertensive disease, but, as demonstrated in certain animal models, EDCF can negatively interact with the L-arginine pathway, causing NO destruction. Thus the present study was designed to evaluate whether cyclooxygenase-dependent EDCF can impair the L-arginine–NO pathway in essential hypertensive patients. Specifically, the investigation focused on assessing whether cyclooxygenase blockade can restore the facilitating or inhibiting effect of L-arginine and L-NMMA, respectively, on the vasodilating response to acetylcholine in essential hypertensive patients.

Methods

Patients

The study population included 14 normotensive control subjects and 14 matched essential hypertensive patients. Subjects with hypercholesterolemia (total cholesterol greater than 5.2 mmol/L), diabetes mellitus, cardiac and/or cerebral ischemic vascular disease, impaired renal function and other major pathologies were excluded from the study. Moreover, subjects or patients smoking more than five cigarettes per day and/or consuming more than 60 g of ethan (corresponding to half a liter of wine) per day were excluded from the study. In accordance with institutional guidelines, all patients were aware of the investigational
nature of the study and gave written consent to it. Any pharmaco-
logical treatment was discontinued for at least 2 weeks before
performing the study.

Subjects, defined as normal according to the absence of fa-
miliar history of essential hypertension and BP below 140/90
mm Hg, were characterized by mean age of 47.6±4.3 years and
BP values of 115.6±6.1/80.3±2.1 mm Hg. Essential hyperten-
sive patients were recruited from among the newly diagnosed
cases in our outpatient clinic if they reported the presence of
positive family history of essential hypertension, whenever sup-
pine arterial BP (after 10 minutes of rest) measured by mercury
sphygmomanometer three times at 1-week intervals was con-
tinuously found greater than 140/90 mm Hg. Secondary forms of
hypertension were excluded by routine diagnostic procedures.

Mean age was 50.6±6.6 years and BP values were 152.5±8.7/
99.2±3.6 mm Hg. Since the patients were newly diagnosed cases,
they were never treated and the known history of hypertension
had lasted 2±0.4 years. The demographic and clinical charac-
teristics of the two groups are shown in the Table

Experimental Procedure

All studies were performed at 0800 AM after overnight fast
with the subjects lying supine in a quiet air-conditioned room
(22°C to 24°C). A polyethylene cannula (21 gauge, Abbott) was
inserted into the brachial artery under local anaesthesia (2% lid-
docaine) and connected through stopcocks (three-way stop-
cocks) to a pressure transducer (Model MS20, Electromedics)
for systemic mean BP (one third pulse pressure-int artostolic pressure) and heart rate monitoring (Model VSM1, Physiocontrol) and for intra-arterial infusions.

FBF was measured in both forearms (experimental and contra-
lateral forearm) by strain-gauge venous plethysmography
(LOOSCO, GL LOOS). Circulation to the hand was excluded
and for intra-arterial infusions cardiac mass, g/m² was measured by ultrasound (Model VSM1, Physiocontrol) and for intra-arterial infusions.

For each measurement, the subjects were instructed to avoid any physical activity for at least 2 hours before the study.

Drugs

Acetylcholine HCl (Farmigena SPA), indomethacin (Liumeta-
cen, Chiesi Farmaceutici SPA), L-arginine (Clinalfa AG),

Characteristics of Study Subjects (mean±SD)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normotensive Subjects (n=14)</th>
<th>Essential Hypertensive Patients (n=14)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>47.6±4.3</td>
<td>50.6±6.6</td>
</tr>
<tr>
<td>Age range, y</td>
<td>39-56</td>
<td>37-61</td>
</tr>
<tr>
<td>Sex, M/F</td>
<td>9/5</td>
<td>10/4</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>72.4±4.1</td>
<td>71.6±5.2</td>
</tr>
<tr>
<td>Systolic BP, mm Hg</td>
<td>115.6±6.1</td>
<td>152.5±8.7</td>
</tr>
<tr>
<td>Diastolic BP, mm Hg</td>
<td>80.3±2.1</td>
<td>99.2±3.5</td>
</tr>
<tr>
<td>Cardiac mass, g/m²</td>
<td>110.6±7.1</td>
<td>116.4±8.4</td>
</tr>
<tr>
<td>Plasma glucose, mg/dL</td>
<td>82.8±6.1</td>
<td>89.4±5.9</td>
</tr>
<tr>
<td>Plasma total cholesterol, mg/dL</td>
<td>186.2±12.3</td>
<td>193.4±12.8</td>
</tr>
<tr>
<td>Plasma HDL cholesterol, mg/dL</td>
<td>42.4±6.8</td>
<td>40.2±6.4</td>
</tr>
<tr>
<td>Plasma LDL cholesterol, mg/dL</td>
<td>118.6±10.2</td>
<td>121.4±11.3</td>
</tr>
<tr>
<td>Body mass index, kg/m²</td>
<td>21.8±0.5</td>
<td>22.1±0.6</td>
</tr>
<tr>
<td>FBF, mL 100 mL⁻¹ min⁻¹</td>
<td>3.4±0.4</td>
<td>3.4±0.5</td>
</tr>
</tbody>
</table>

HDL indicates high-density lipoprotein, LDL, low-density lipoprotein
L-NMMA (Clinalfa AG), and sodium nitroprusside (Malescl) were obtained from commercially available sources and diluted freshly to the desired concentration by adding normal saline. Sodium nitroprusside was dissolved in glucosate solution and protected from light by aluminum foil.

**Results**

**Response to Intrabrachial Acetylcholine and Sodium Nitroprusside**

In the overall population, vasodilation to acetylcholine was significantly ($P<0.01$) blunted in essential hypertensive patients (FBF rose from 3.4±0.5 to a maximum of 17.1±3.2 mL/100 mL forearm tissue per minute with the highest dose) compared with normotensive control subjects (FBF rose from 3.4±0.4 to a maximum of 23.9±5.4 mL/100 mL forearm tissue per minute with the highest dose) (Fig 1). In contrast, the vasodilating effect of the endothelium-independent vasodilator sodium nitroprusside was similar in normotensive subjects and essential hypertensive patients (FBF rose from 3.6±0.4 to a maximum of 24.1±2.9 mL/100 mL forearm tissue per minute with the highest dose and from 3.5±0.4 to a maximum of 23.3±3.1 mL/100 mL forearm tissue per minute, respectively, NS) (Fig 1).

**Effect of Cyclooxygenase Inhibition on Response to Acetylcholine in the Presence of L-NMMA**

In this group of normotensive control subjects, L-NMMA infusion caused a decrement in basal FBF (from 3.4±0.4 to 1.9±0.2 mL/100 mL forearm tissue per minute; $P<0.01$) and significantly blunted the vasodilating effect of acetylcholine (saline: from 3.4±0.4 to 26.2±5.6 mL/100 mL forearm tissue per minute, L-NMMA from 1.9±0.2 to 8.3±2.1 mL/100 mL forearm tissue per minute, $P<.01$ versus acetylcholine alone) (Fig 2). Again indomethacin did not change either basal FBF (from 3.4±0.4 to 3.4±0.4 mL/100 mL forearm tissue per minute), the response to acetylcholine (from 3.4±0.4 to 26.8±5.4 mL/100 mL forearm tissue per minute), or the inhibiting effect of L-NMMA on vasodilation to acetylcholine (from 1.9±0.2 to 8.3±2.5 mL/100 mL forearm tissue per minute) (Fig 2).

In the essential hypertensive patients, L-NMMA infusion caused a decrement in basal FBF (from 3.2±0.5 to 2.3±0.5 mL/100 mL forearm tissue per minute, $P<0.01$) which was significantly smaller than that observed in normotensive control subjects (percent FBF decrease 44% versus 28%, respectively, $P<0.01$). However, the response to acetylcholine (from 3.2±0.5 to 17.7±4.2 mL/100 mL forearm tissue per minute) was not changed by L-NMMA (from 2.3±0.5 to 12.5±3.2 mL/100 mL forearm tissue per minute, NS versus saline) (Fig 2). Indomethacin infusion did not change basal FBF (from 3.1±0.4 to 3.1±0.6 mL/100 mL forearm tissue per minute) Nevertheless, the cyclooxygenase inhibitor increased the response to acetylcholine (from 3.1±0.4 to 22.0±3.3 mL/100 mL forearm tissue per minute, $P<0.01$ versus acetylcholine during saline) (Fig 2). Finally, when the effect of L-NMMA was tested in the presence of indomethacin, the NO synthase inhibitor blunted the vasodilating response to acetylcholine (from 2.3±0.5 to 12.5±3.7 mL/100 mL forearm tissue per minute, $P<0.01$ versus acetylcholine during indomethacin alone) (Fig 2).
Different results were obtained in essential hypertensive patients. Again acetylcholine infusion caused a dose-dependent vasodilatation (from 3.6±0.5 to 16.4±2.9 mL/100 mL forearm tissue per minute) which was statistically lower (P<.01) than that observed in normotensive control subjects. L-Arginine administration changed neither basal FBF (from 3.6±0.5 to 3.7±0.4 mL/100 mL forearm tissue per minute) or the vasodilating effect of acetylcholine (from 3.7±0.4 to 16.5±3.1 mL/100 mL forearm tissue per minute, NS versus saline) (Fig 3). Indomethacin did not change basal FBF (from 3.0±0.5 to 3.4±0.4 mL/100 mL forearm tissue per minute), but significantly increased the response to acetylcholine (from 3.4±0.4 to 23.6±3.4 mL/100 mL forearm tissue per minute, P<.01 versus saline) (Fig 2). It is worth noting, finally, that when L-arginine was infused with indomethacin the vasodilating effect of acetylcholine was further increased (from 3.4±0.5 to 31.1±4.1 mL/100 mL forearm tissue per minute, P<.01 versus acetylcholine in the presence of indomethacin) (Fig 3).

In both normotensive subjects and essential hypertensive patients contralateral FBF did not significantly change during the whole study (data not shown).

**Discussion**

Essential hypertension is characterized by endothelial dysfunction.11-18 This alteration is further confirmed in the present study since the response to acetylcholine, an endothelium-dependent vasodilator,1,5,22 but not to sodium nitroprusside, a direct smooth muscle cell relaxant,23 was blunted in essential hypertensive patients compared with matched normotensive control subjects. The mechanisms responsible for the impaired endothelium-dependent vasodilatation include an alteration in the L-arginine—NO pathway and production of cyclooxygenase-dependent EDCF. That these mechanisms can operate in essential hypertensive patients is confirmed by the present results. Thus, in agreement with previous observations,19 administration of L-arginine, the substrate for NO synthase,3 can increase the vasodilating effect of acetylcholine in normotensive subjects while the amino acid is ineffective in essential hypertensive patients. Moreover, L-NMMA, an antagonist for NO synthase,4,5 can blunt the response to acetylcholine in control subjects, but not in hypertensive patients.15 Taken together these results clearly confirm the presence of a defect in the endothelium-derived NO system in essential hypertension, since neither activation nor inhibition of the NO pathway can lead to modifications of the vascular response to the endothelium-dependent vasodilator. It is important to observe that the lack of effect of these compounds on acetylcholine-induced vasodilatation is not linked to insufficient infusion rates of either L-arginine or L-NMMA, as already demonstrated by previous evidence obtained in similar experimental conditions.16,17 Moreover, this abnormality does not totally account for the impaired vasodilatation to acetylcholine observed in essential hypertension. Thus in hypertensive patients, but not in normotensive subjects, indomethacin increased the response to the endothelium-dependent vasodilator, confirming that, in agreement with previous evidence,15 the production of cyclooxygenase derivatives can curtail endothelial responses in essential hypertension. It is worth noting that for the first time the alteration in the endothelium-derived NO system and production of cyclooxygenase-dependent EDCF has been demonstrated in the same
patients, supporting the possibility that these endothelial alterations coexist in essential hypertension.

However, the main finding of the present study is the demonstration that in essential hypertensive patients cyclooxygenase activity causes endothelial dysfunction by producing cyclooxygenase-dependent substances which, at least partially, can inactivate the L-arginine–NO system. 

There is experimental evidence indicating that in vessels from hypertensive animals a close relationship exists between the L-arginine–NO pathway and cyclooxygenase activity. Thus in primary hypertension, cyclooxygenase activity is increased to produce not only vasoconstrictor prostanooids, but also superoxide anions, which cause NO breakdown. Moreover, it has been demonstrated in canine basilar arteries that an increased production of superoxide anions can destroy NO produced by the activity of the L-arginine pathway, thus causing full expression of vasoconstrictor prostanooids. This negative interaction between the NO system and cyclooxygenase activity could lead to the production of NO-inactivating substances (endoperoxides? superoxide anions?), thus explaining the absence of effects of L-arginine and L-NMMA on vasodilation to acetylcholine. When cyclooxygenase is blocked by indomethacin and NO breakdown no longer occurs or is at least decreased, it is therefore possible to demonstrate the activity of L-arginine and L-NMMA as observed in normotensive control subjects.

The relationship between cyclooxygenase-dependent EDCF and primary hypertension is of interest. It must be noted that these substances, while causing endothelial dysfunction, do not seem to contribute to an increase in BP values. Thus, in the spontaneously hypertensive rat, treatment by ifetroban, a thromboxane A2/prostaglandin endoperoxide-receptor blocker, normalized endothelium-dependent relaxations to acetylcholine in isolated segments of aorta but produced no reduction in BP values. In agreement with experimental data, in human hypertension the acute administration of nifedipine, a combined thromboxane synthase inhibitor and thromboxane A2 receptor antagonist, did not lower BP values in essential hypertensive patients. In addition, the lack of relationship between cyclooxygenase-dependent EDCF and BP values in humans is further confirmed by recent evidence indicating that production of such substances seem to be mainly related to the aging process. Thus in normotensive subjects it is possible to detect production of EDCF when aging increases over 60 years, and this phenomenon is even more heightened in essential hypertensive patients (arterial hypertension from the fourth decade of life). However, it is worth noting that in young essential hypertensive patients production of cyclooxygenase-dependent EDCF does not seem to occur

Therefore, the dissociation between EDCF production and elevated BP values underlines the possibility that EDCF do not participate in the development of hypertension. However, it is well documented that whatever is the nature of EDCF (endoperoxide or superoxide anions), they can increase vascular tone and stimulate platelet aggregation or smooth muscle cell proliferation by direct mechanisms or by inducing NO breakdown. It is therefore conceivable that EDCF production, although not important as a causal mechanism responsible for the development of hypertension, probably plays a role in the vascular damage associated with aging and hypertension itself.

As regards the important issue of the relationship between the duration of essential hypertension and EDCF production, no data are available to understand whether the degree of synthesis of these substances is in some way dependent on the length of the hypertensive process. In the present study, unfortunately the recruited hypertensive population shows a quite short duration of hypertension and no conclusion can be drawn.

Finally, it is worth noting that these endothelial mechanisms operate mainly when endothelial cells are stimulated by acetylcholine. Thus, in agreement with previous observations, neither L-arginine nor indomethacin (nor the combination of both compounds) can influence basal blood flow in either normotensive subjects or essential hypertensive patients. In contrast, L-NMMA infusion can decrease basal FBF, confirming that NO is basally released in human vasculature and this mechanism is defective in essential hypertension since, as previously demonstrated, L-NMMA–induced vasoconstriction is blunted in hypertensive patients compared with control subjects. However, the simultaneous infusion of indomethacin with L-NMMA does not change the vasoconstrictor effect of the NO synthase inhibitor suggesting that cyclooxygenase activity does not participate in NO-mediated regulation of basal flow.

In conclusion, the present results indicate that endothelial dysfunction which is characteristic of essential hypertension is determined by the simultaneous presence of an alteration in the L-arginine–NO pathway and production of cyclooxygenase derivatives. These alterations do not seem to be independent since in essential hypertensive patients, but not in normotensive control subjects, the dysfunctional NO system seems to be restored or at least improved by cyclooxygenase blockade. Which cyclooxygenase-dependent substances could be responsible for inhibition of the L-arginine NO pathway is, at the present time, under investigation.

References

8 Shirahase H, Fujimura M, Usui H, Kurihoshi K A possible role of thromboxane A2 in endothelium in maintaining resting tone and producing constriction response to acetylcholine and arachidonic acid in canine cerebral artery *Blood Vessels* 1987,24 117-119
9 Kato T, Iwama Y, Okanura K, Hashimoto H, Ito T, Satake T Prostaglandin H2 may be the endothelium-derived contracting factor released by acetylcholine in the aorta of the rat *Hypertension* 1990,15 475-482
11 Lunder L, Kiowski W, Buhler FR, Luscher TF Indirect evidence for the release of endothelium derived relaxing factor in the human forearm circulation in vivo blunted response in essential hypertension *Circulation* 1990,81 1762-1767
13 Taddei S, Virdis A, Mattel P, Salvetti A Vasodilation to acetylcholine in primary and secondary forms of human hypertension *Hypertension* 1993,21 929-933
14 Taddei S, Virishi A, Mattel P, Ghidoni L, Gennari A, Basile Fusolo C, Sudano I, Salvetti A Aging and endothelial function in normoten-}

15 Panza JA, Garcia CE, Kilcoyne CM, Quyyumi A, Cannon RO III Impaired endothelium-dependent vasodilation in patients with essential hypertension evidence that nitric oxide availability is not localized to a single signal transduction pathway *Circulation* 1995,91 1732-1738
16 Panza JA, Casino PR, Badar DM, Quyyumi AA Effect of increased availability of endothelium-derived nitric oxide precursor on endothelium-dependent vascular relaxation in normal subjects and in patients with essential hypertension *Circulation* 1993,87 1475-1481
17 Panza JA, Casino PR, Kilcoyne CM, Quyyumi AA Role of endothelium-derived nitric oxide in the abnormal endothelium-dependent vascular relaxation of patients with essential hypertension *Circulation* 1993,87 1468-1474
18 Taddei S, Virdis A, Mattei P, Natal A, Ferranuzzi E, Salvetti A Effect of insulin on acetylcholine-induced vasodilation in normoten-

sive subjects and patients with essential hypertension *Circulation* 1995,92 2911-2918
19 Cosentino F, Still JC, Katsue ZS Role of superoxide anions in the mediation of endothelium-dependent contraction *Hypertension* 1994,23 220-235
20 Whitney KJ The measurement of volume changes in human limbs *J Physiol (Lond)* 1953,121 1-27
21 Pedrelli R, Taddei S, Gaziadei L, Salvetti A Vascular responses to ouabain and norepinephrine in low and normal ren hypertension *Hypertension* 1986,8 786-792
22 Furchgott RF, Zawadzki JV The obligatory role of endothelial cells in the relaxation of arterial smooth muscle by acetylcholine *Nature* 1980,288 373-376
23 Schultz KD, Schultz K, Schultz G Sodium nitroprusside and other smooth muscle relaxants increase cyclic GMP levels in rat ductus deferens *Nature* 1977,265 750-751
24 King CF, Lüscher TF Different mechanisms of endothelial dysfuction with aging and hypertension in rat aorta *Hypertension* 1995,25 194-200
26 Gryglewski RJ, Palmer RMJ, Moncada S Superoxide anion plays a role in the breakdown of endothelium-derived relaxing factor *Nature* 1986,320 454-456
31 Calver A, Collier J, Moncada S, Vallance P Effect of local intrarteral N\(^{\text{6}}\)monomethyl-L-arginine in patients with essential hypertension the nitric oxide deitator mechanism appears abnormal *J Hypertens* 1992,10 1025-1031
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