Abstract—We examined the influence of interactions between CO and 20-hydroxyeicosatetraenoic acid (20-HETE) on vascular reactivity to phenylephrine and vasopressin. Renal interlobar arteries incubated in Krebs buffer released CO at a rate that is decreased (from 125.0±15.2 to 46.3±8.8 pmol/mg protein per hour, P<0.05) by the heme oxygenase inhibitor chromium mesoporphyrin (CrMP; 30 μmol/L). The level of 20-HETE in vessels was not affected by CrMP (74.3±6.1 versus 72.5±16.2 pmol/mg protein), but was decreased (P<0.05) by CO (1 μmol/L; 33.2±7.9 pmol/mg protein) or the cytochrome P450–4A inhibitor N-methylsulfonyl-12,12-dibromododec-11-enamide (DDMS; 30 μmol/L; 11.4±3.3 pmol/mg protein). Phenylephrine elicited development of isometric tension in vascular rings mounted on a wire-myograph (EC\textsubscript{50}, 0.29±0.02 μmol/L; R\textsubscript{max}, 3.78±0.19 mN/mm). The sensitivity to phenylephrine was decreased (P<0.05) by CO (1 μmol/L; EC\textsubscript{50}, 0.60±0.04 μmol/L) or DDMS (EC\textsubscript{50}, 0.71±0.12 μmol/L) and increased (P<0.05) by 20-HETE (10 μmol/L; EC\textsubscript{50}, 0.08±0.02 μmol/L) or CrMP (EC\textsubscript{50}, 0.11±0.02 μmol/L). Notably, neither CO nor CrMP changed the sensitivity to phenylephrine in vessels treated with DDMS. Refractoriness to CO and CrMP in such a setting was eliminated by inclusion of 20-HETE (1 μmol/L) in the bathing buffer. The aforementioned interventions affected the vascular reactivity to vasopressin in a similar manner. These data indicate that the reactivity of renal arteries to phenylephrine and vasopressin is reciprocally influenced by CO and 20-HETE of vascular origin and that CO desensitizes the vascular smooth muscle to constrictor agonists by interfering with the sensitizing influence of 20-HETE. (Hypertension. 2004;44:210-216.)

Key Words: adrenergic receptor agonists ■ vasopressins ■ potassium channels ■ renal circulation

Recent studies indicate that CO and 20-hydroxyeicosatetraenoic acid (20-HETE) of vascular origin influence the reactivity of rat arterial vessels to constrictor agonists in divergent directions.1–3 CO, a product of heme metabolism by heme oxygenase (HO) isoforms –1 and –2,3 reduces the sensitivity of vascular smooth muscle to phenylephrine and vasopressin.1 In contrast, 20-HETE, a product of arachidonic acid ω-hydroxylation by isoforms of the cytochrome P450 4A family (CYP4A),4,5 increases the sensitivity of vascular smooth muscle to phenylephrine2 and vasopressin.3 The reciprocal modulatory actions of CO and 20-HETE on vascular reactivity to phenylephrine are linked, respectively, to stimulation and inhibition of large conductance calcium-activated potassium (K\textsubscript{Ca}) channels in vascular smooth muscle.1,5–8

In view of the aforementioned observations, it is conceivable that the sensitivity of arterial vessels to constrictor agonists is determined, at least in part, by the interplay between CO and 20-HETE manufactured by the vessels. One possibility is that the modulatory interplay simply results from the balance between regulatory substances with opposite actions on vascular reactivity. Another possibility is that the inhibitory action of CO on vasomotor responsiveness to phenylephrine relies on interference with the vascular production of 20-HETE. The latter possibility is supported by reports that CO inhibits many cytochrome P450 enzymes, including the CYP4A isoforms that catalyze 20-HETE synthesis.5,9

This study was undertaken to test the hypothesis that an interplay between CO and 20-HETE of vascular origin influences the reactivity of renal vascular smooth muscle to phenylephrine and vasopressin. We examined whether vascular CO influences the production of vascular 20-HETE. We also examined whether the ability of CO and HO inhibitors to decrease and increase, respectively, the sensitivity of rat renal interlobar arteries to phenylephrine and vasopressin is influenced by the status of 20-HETE synthesis or the level of exogenous 20-HETE.

Methods

Chemicals and Solutions

20-HETE and the CYP4A inhibitor N-methylsulfonyl-12,12-dibromododec-11-enamide (DDMS) were synthesized by J.R.
Falck,10 and stock solutions were prepared using punctilious ethanol. The HO inhibitor chromium mesoporphyrin (CrMP) was purchased from Porphyran (Boehringer). CrMP and stock solutions were prepared in 50 mmol/L Na2CO3. CO was purchased from Tech Air and a saturated solution (1 mmol/L) was prepared using ice-cold Krebs buffer composed of (in mmol/L) 118.5 NaCl, 4.7 KCl, 2.5 CaCl2, 1.2 KH2PO4, 1.2 MgSO4, 25.0 NaHCO3, and 11.1 dextrose. All other chemicals were obtained from Sigma.

Animals
Studies were conducted on male Sprague-Dawley rats (body weight 250 to 300 g; Charles-River, Wilmington, Mass) according to protocols approved by the Institutional Animal Care and Use Committee. Rats were anesthetized with pentobarbital sodium (60 mg/kg, IP), the kidneys were excised and sectioned sagittally, and the interlobar arteries were dissected out for immediate use in studies on production of 20-HETE and CO, contractile responsiveness to agonists, and assessment of K+ currents in vascular smooth muscle cells.

Assessment of 20-HETE Production
Renal interlobar artery specimens were transferred into glass vials (5 mL) containing 1 mL of Krebs buffer saturated with 95% O2-5% CO2 and complemented with NADPH (1 mmol/L), N-nitro-l-arginine methyl ester (l-NAME; 1 mmol/L) and indomethacin (10 μmol/L). The vials were capped tightly with rubberized Teflon liners, and the samples were incubated at 37°C for 60 minutes in the absence and presence of DDMS (30 μmol/L), CrMP (30 μmol/L), or CO (1 μmol/L). At the end of the incubation period, both media and vessels were extracted with acidified ethyl acetate (pH 4.0) and the organic phase was evaporated to dryness. The 20-HETE present in the extract was purified by reverse-phase high-pressure liquid chromatography on a C18 Beckman Ultrasphere column (4.6 mm × 24 cm; 5 μm particle size) using a linear gradient from acetonitrile:water:acetic acid (75:25:0.05) to acetonitrile (100%) over 20 minutes at a flow rate of 1 mL/min. Fractions containing 20-HETE were dried under N2 and derivatized for quantification by negative chemical ionization gas chromatography–mass spectroscopy according to a published method.11

Assessment of CO Production
Renal interlobar artery specimens were transferred into amber vials (2 mL) containing 1.0 mL of Krebs buffer saturated with 95%O2-5% CO2, the vials were capped tightly with rubberized Teflon liners, and the samples were incubated at 37°C for 60 minutes in the absence and presence of CrMP (30 μmol/L). Subsequently, internal standards made of isotopically labeled CO (13C6O and 15C6O) were injected into samples, and the CO content of the headspace gas was determined by gas chromatography–mass spectroscopy analysis according to a published method.11

Assessment of Agonist-Induced Vascular Contraction
Renal interlobar arteries were cut into ring segments (2 mm in length) and mounted on 25-μm stainless steel wires in the chambers of a myograph (J.P. Trading) for measurement of isometric tension in rings of rat renal interlobar arteries.1 The experiments were conducted within 4 hours of completing isolation of the cells, using the patch-clamp technique in the cell-attached configuration as previously described.1 Open-state probability (NPo) was calculated from data sampled over a 30- to 60-second interval in the steady state during control and experimental periods.1 Recordings were conducted during the control period and during sequential exposure of the vascular smooth muscle cells to DDMS (30 μmol/L) only, DDMS plus 20-HETE (1 μmol/L), and CO (10 μmol/L) in combination. As previously reported,1 a 105-pS K channel was identified in cell-attached patches of renal interlobar arteries. The activity of this channel is inhibited by TEA (0.1 mmol/L) and stimulated by exposure to Ca2+.1

Data Analysis
Data are expressed as means±SEM. Concentration-response data were fitted to a logistic function by nonlinear regression, and the model data sampled over a 30- to 60-second interval in the steady state during control and experimental periods.1 Recordings were conducted during the control period and during sequential exposure of the vascular smooth muscle cells to DDMS (30 μmol/L) only, DDMS plus 20-HETE (1 μmol/L), and DDMS plus 20-HETE and CO (10 μmol/L) in combination. As previously reported,1 a 105-pS K channel was identified in cell-attached patches of renal interlobar arteries. The activity of this channel is inhibited by TEA (0.1 mmol/L) and stimulated by exposure to Ca2+.1

Results
Production of CO and 20-HETE by Renal Interlobar Artery
Renal interlobar arteries released CO into the headspace during incubation in Krebs buffer (125.0±15.2 pmol/mg protein per hour; n=6); the amount released decreased (P<0.05) to ~37% of control when the vessels were incubated in buffer containing the HO inhibitor CrMP (30 μmol/L, 46.3±8.8 pmol/mg protein per hour; n=6). The level of 20-HETE in renal interlobar arteries incubated for 60 minutes in Krebs buffer was 74.3±6.1 pmol/mg protein (n=7), decreasing (P<0.05) to ~15% of control when the vessels were incubated in buffer containing DDMS (30 μmol/L, 11.4±3.3 pmol/mg protein; n=6). The level of 20-HETE also was reduced (P<0.05) in renal interlobar arteries incubated in buffer containing CO (1 μmol/L, 33.2±7.9 pmol/mg protein; n=6), but was unchanged in vessels incubated in buffer containing CrMP (30 μmol/L, 72.5±16.2 pmol/mg protein; n=8).

CO and 20-HETE as Determinants of Renal Vascular Reactivity to Phenylephrine
Phenylephrine elicited concentration-dependent augmentation of isometric tension in rings of rat renal interlobar arteries. Figure 1 illustrates the effects of CO and 20-HETE, alone and in combination, on contractile responsiveness to phenylephrine in arteries bathed in media without (Figure 1A) and with (Figure 1B) DDMS (30 μmol/L). The concentration-response curve to phenylephrine was shifted to the right in vessels exposed to DDMS only, resulting in augmentation of the phenylephrine EC50 (from 0.29±0.02 to...
CYP4A inhibitor and 20-HETE (from 0.14±0.01 to 0.44±0.06 μmol/L). The \( R_{\text{max}} \) for phenylephrine was not affected by 20-HETE, CO, or both substances combined in either vessels exposed or not exposed to DDMS.

As shown in Figure 2, treatment of renal interlobar artery rings with TEA produced, like treatment with 20-HETE alone, a leftward displacement in the concentration-response curve to phenylephrine and a reduction of \( EC_{50} \) values \((P<0.05)\) without altering the maximal response. The sensitization to phenylephrine in TEA-treated vessels was not enhanced further by concurrent treatment with 20-HETE. Moreover, exogenous CO did not decrease the sensitivity to phenylephrine in vessels pretreated with both TEA and 20-HETE.

Figure 3 (top graph) illustrates the effects of CrMP (30 μmol/L), alone and in combination with DDMS (30 μmol/L), on contractile responsiveness to phenylephrine. The HO inhibitor CrMP elicited a leftward shift in the concentration-response curve to phenylephrine in vascular preparations not exposed to the CYP4A inhibitor DDMS, decreasing \((P<0.05)\) the \( EC_{50} \) from 0.31±0.01 to 0.11±0.02 μmol/L. In contrast, CrMP did not decrease the \( EC_{50} \) for phenylephrine in preparations exposed to DDMS (0.49±0.05 versus 0.52±0.04 μmol/L). Yet, CrMP did decrease \((P<0.05)\) the \( EC_{50} \) for phenylephrine in vessels concurrently exposed to DDMS and 20-HETE (1 μmol/L) from 0.30±0.04 to 0.13±0.02 μmol/L. 20-HETE at 1 μmol/L was effective in offsetting the desensitizing effect of DDMS, decreasing \((P<0.05)\) the \( EC_{50} \) for phenylephrine from 0.49±0.05 μmol/L in vessels treated with DDMS only to 0.30±0.04 μmol/L in vessels treated concurrently with DDMS and 20-HETE, which is not different from that value obtained in control untreated vessels (0.31±0.01 μmol/L).

The \( R_{\text{max}} \) for phenylephrine was not affected by any of the aforementioned experimental manipulations.
**CO and 20-HETE as Determinants of Renal Vascular Reactivity to Vasopressin**

Figure 4 shows data on the effects of CO (1 μmol/L) and 20-HETE (10 μmol/L), alone and in combination, on responsiveness to vasopressin in renal interlobar arteries bathed in buffer alone and buffer containing either DDMS (30 μmol/L), CrMP (30 μmol/L), DDMS plus CrMP, DDMS plus 20-HETE (1 μmol/L), or DDMS plus 20-HETE plus CrMP. Results are mean±SEM, n=number of experiments. *P<0.05 relative to control.

**Reciprocal Influence of 20-HETE and CO on K Channel Currents in Smooth Muscle Cells of Renal Interlobar Arteries**

As shown in Figure 5, cell-attached patches display little or no K⁺ channel activity in smooth muscle cells bathed in control media (NPo, 0.03±0.02; n=4). Addition of the CYP4A inhibitor DDMS (30 μmol/L) to the bath greatly
Rat renal interlobar arteries incubated in Krebs buffer were
bathed in media containing (in mmol/L) 140 NaCl, 5 HCl, 1.8
MgCl₂, 1.8 CaCl₂, and 10 HEPES (pH 7.4). The holding potential
was 0.0 mV. The channel closed level is indicated by C. The top
recording shows the time course of the experiment; the seg-
ments of the recording indicated by the numbers 1 to 4 are pre-
1
2
3
4
presented below at fast time resolution.

Figure 5. Channel recording showing the effect of DDMS
(30 μmol/L) alone, DDMS plus 20-HETE (1 μmol/L), and DDMS
plus 20-HETE plus CO (10 μmol/L) on the activity of Keselect
channels in a smooth muscle cell isolated from rat renal interlobar
artery. The experiment was performed in a cell-attached patch
bathed in media containing (in mmol/L) 140 NaCl, 5 HCl, 1.8
MgCl₂, 1.8 CaCl₂, and 10 HEPES (pH 7.4). The holding potential
was 0.0 mV. The channel closed level is indicated by C. The top
recording shows the time course of the experiment; the seg-
ments of the recording indicated by the numbers 1 to 4 are pre-
1
2
3
4
presented below at fast time resolution.

stimulated (P<0.05) channel activity (NP₀, 1.67±0.03; n=4). In the face of continuous exposure of the cells to
DDMS, K⁺ channel activity decreased (NP₀, 0.30±0.19; n=4, P<0.05) following the addition of exogenous 20-HETE to the media (1 μmol/L). In the face of continuous exposure to DDMS and 20-HETE, K⁺ channel activity was increased (NP₀, 1.20±0.23; n=4, P<0.05) on the inclusion of exoge-

Discussion
This study provides information on the influence of CO on vascular 20-HETE production and on whether vasoregulatory
mechanisms involving CO and 20-HETE are interconnected.

The salient conclusion derived from the study is that an
interplay between CO and 20-HETE of vascular origin
regulates constrictor responsiveness to phenylephrine and
vasopressin in rat renal interlobar arteries.

Rat renal interlobar arteries incubated in Krebs buffer were
found to manufacture CO and 20-HETE. Confirming a
previous report, vascular CO production was inhibited by
CrMP, which is suggestive of HO dependency. The level of
20-HETE in renal interlobar arteries was reduced by treatment
with DDMS, implying that vascular 20-HETE produc-
tion is dependent on the activity of 1 or more CYP4A
oxygenases. CO is known to interfere with the activity of cytochrome P450 enzymes and therefore is expected to
decrease 20-HETE synthesis. In keeping with this notion, we
found that the level of 20-HETE falls in renal interlobar
arteries incubated in buffer containing exogenous CO (1 μmol/L). However, 20-HETE levels were not increased in
vessels treated with CrMP. The fact that inhibition of vascular
HO with CrMP is without effect on vascular 20-HETE levels
implies that basal levels of endogenous CO are inconsequent-
tial to 20-HETE synthesis. This may not be the case in
pathophysiological states featuring increased expression or
activity of HO isoforms leading to enhanced vascular pro-
duction of CO. It is plausible that in such settings the vascular
production of 20-HETE is subject to inhibitory regulation by
CO of vascular origin.

Observations that the sensitivity of renal interlobar arteries
to phenylephrine and vasopressin is reciprocally influenced
by CO and 20-HETE are central to the notion that an inter-
play between these substances regulates the reactivity of renal
vascular smooth muscle to constrictor agonists. In this regard,
we confirmed previous reports that the sensitivity of small
arteries to phenylephrine and vasopressin is decreased by
exogenous CO and increased by exogenous 20-HETE. The
reactivity of the vessels to the constrictor agonists also is
decreased and increased, respectively, by CO and 20-HETE
manufactured by the renal vessels themselves because their
sensitivity to phenylephrine and vasopressin was found to
increase in response to HO inhibition with CrMP and to
decrease after CYP4A inhibition with DDMS. Notably,
either exogenous CO nor CrMP affected changes in respon-
siveness to the constrictor agonist in vascular preparations
undergoing CYP4A inhibition with DDMS. Refractoriness to
CO and the HO inhibitor in DDMS-treated vessels was
eliminated by the inclusion of authentic 20-HETE in the
bathing buffer. Hence, these findings suggest that the ability
of CO to reduce the sensitivity of rat renal interlobar arteries
to phenylephrine and vasopressin is linked to interference
with 20-HETE–induced sensitization of the vessels to the
constrictor agonists, rather than to inhibition of vascular
production of 20-HETE.

K⁺ channels in vascular smooth muscle participate in the
regulation of membrane potential and hence vascular tone
and reactivity. Previous studies established that the activity
of K⁺ channels in small arterial vessels is reduced by
exogenous 20-HETE and increased by exogenous CO. The
activity of K⁺ channels, respectively, because the open state probability of the channel(s) was shown to increase and
decrease during treatment with a CYP4A inhibitor and a HO inhibitor, respectively. According to the present study, in renal interlo-
bar arteries smooth muscle cells undergoing inhibition of
20-HETE synthesis with DDMS, treatment with exogenous
20-HETE suppressed K⁺ channel activity; this effect was
offset by concurrent exposure of the cells to exogenous CO. Such an interplay between 20-HETE and CO at the level of KCa channels in vascular smooth muscle may explain the reciprocal regulatory influence of these substances on vascular reactivity to constrictor agonists. In this respect, we found that blockade of KCa channels with TEA increases the sensitivity of renal interlobar arteries to phenylephrine, mimicking the sensitizing influence of 20-HETE. Sensitization to this constrictor agonist in TEA-treated vessels was not enhanced further by concurrent treatment with 20-HETE, nor was the degree of sensitization obtained under such condition diminished by the inclusion of exogenous CO into the bathing buffer. Hence, the ability of CO to counteract 20-HETE–induced sensitization of renal interlobar arteries to phenylephrine appears to rely on its capacity to offset the inhibitory action of the eicosanoid on KCa channel activity.

There is paucity of information on the molecular mechanisms underlying the interplay of 20-HETE and CO in relation to the regulation of KCa channel activity in vascular smooth muscle cells. Inhibition of KCa channel activity by 20-HETE was shown to rely on a mechanism involving protein kinase C (PKC) in cerebral vascular smooth muscle and tyrosine kinase in smooth muscle cells obtained from renal interlobular arteries. Stimulation of vascular smooth muscle KCa channel activity by CO was attributed to increased sensitivity of the channel to calcium, along with enhanced coupling of calcium sparks to KCa channels. CO-induced stimulation of vascular KCa channels does not rely on increased formation of cGMP. No information is available on whether the stimulatory action of CO on KCa channels depends on interference with the PKC- or tyrosine kinase–mediated mechanism that reportedly is central to the inhibitory action of 20-HETE on KCa channel activity.

In summary, this study demonstrates that an interplay between CO and 20-HETE manufactured by rat renal interlobar arteries influences the reactivity of the vessels to the constrictor action of phenylephrine and vasopressin. We found that the ability of CO to reduce the vascular sensitivity to these agents is linked to interference with 20-HETE–induced sensitization of the vessels to agonist-induced vasoconstriction. We also found that the desensitizing action of CO relies on its capacity to stimulate KCa channel activity in vascular smooth muscle and, thus, offset the inhibitory action of 20-HETE on the KCa channel. Our study, suggests that the interaction between CO and 20-HETE of vascular origin influences the reactivity of the renal vasculature to constrictor stimuli and, thus, may contribute to the regulation of renal hemodynamic function.

Perspectives
The notion that the HO–CO and CYP4A–20-HETE systems are functionally coupled merits special consideration in view of evidence implicating CO and 20-HETE of renal origin in the regulation of renal circulatory functions. For example, intrarenal generation of an HO product, presumably CO, was shown to support blood flow to the kidney by counteracting constrictor mechanisms dependent on the sympathetic nervous and renin–angiotensin systems. On the other hand, intrarenal generation of 20-HETE was reported to promote renal vasoconstriction via amplification of constrictor mechanisms involving myogenic and neurohormonal stimuli. If, as suggested in the present study, CO serves as a counterbalancing influence to the sensitizing action of 20-HETE on responsiveness to constrictor stimuli, conditions in which vascular CO generation is compromised may also feature reduction of renal blood flow because of amplification of 20-HETE–induced sensitization of the renal vasculature to prevailing constrictor mechanisms. Such may be the case of young spontaneously hypertensive rats, animals which were shown to display diminished vascular HO activity and greatly increased responsiveness to the sensitizing action of 20-HETE on phenylephrine-induced constriction of small arterial vessels. The HO–CO and CYP4A–20-HETE systems also may be functionally coupled in relation to their regulatory functions in extrarenal circulatory beds.

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Vascular CO Counterbalances the Sensitizing Influence of 20-HETE on Agonist-Induced Vasoconstriction

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