Astrocyte-Derived CO Is a Diffusible Messenger That Mediates Glutamate-Induced Cerebral Arteriolar Dilation by Activating Smooth Muscle Cell K$_{Ca}$ Channels

Anlong Li, Qi Xi, Edward S. Umstot, Lars Bellner, Michal L. Schwartzman, Jonathan H. Jaggar, Charles W. Leffler

Abstract—Astrocyte signals can modulate arteriolar tone, contributing to regulation of cerebral blood flow, but specific intercellular communication mechanisms are unclear. Here we used isolated cerebral arteriole myocytes, astrocytes, and brain slices to investigate whether carbon monoxide (CO) generated by the enzyme heme oxygenase (HO) acts as an astrocyte-to-myocyte gasotransmitter in the brain. Glutamate stimulated CO production by astrocytes with intact HO-2, but not those genetically deficient in HO-2. Glutamate activated transient K$_{Ca}$ currents and single K$_{Ca}$ channels in myocytes that were in contact with astrocytes, but did not affect K$_{Ca}$ channel activity in myocytes that were alone. Pretreatment of astrocytes with chromium mesoporphyrin (CrMP), a HO inhibitor, or genetic ablation of HO-2 prevented glutamate-induced activation of myocyte transient K$_{Ca}$ currents and K$_{Ca}$ channels. Glutamate decreased arteriole myocyte intracellular Ca$^{2+}$ concentration and dilated brain slice arterioles and this decrease and dilation were blocked by CrMP. Brain slice arteriole dilation to glutamate was also blocked by L-2-alpha aminoadipic acid, a selective astrocyte toxin, and paxilline, a K$_{Ca}$ channel blocker. These data indicate that an astrocytic signal, notably HO-2–derived CO, is used by glutamate to stimulate arteriole myocyte K$_{Ca}$ channels and dilate cerebral arterioles. Our study explains the astrocyte and HO dependence of glutamatergic functional hyperemia observed in the newborn cerebrovascular circulation in vivo. (Circ Res. 2008;102:234-241.)

Key Words: newborn ■ cerebrovascular circulation ■ functional hyperemia ■ heme oxygenase

Local cerebral arteriole smooth muscle tone is temporally and spatially coordinated to match blood flow to neuronal activity. This vascular response is termed functional hyperemia or neurovascular coupling.1,2 In the cerebrovascular circulation, signals to vascular smooth muscle cells derive from astrocytes, macrophages, or pericytes, which interact to form a neurovascular unit.3 Astrocytes relay signals to neurons and other astrocytes.4,5,6 Parenchymal arterioles are ensheathed by astrocyte endfeet.7,8 Pial arterioles lay on a bed of astrocytes, the glia limitans, and astrocyte processes and endfeet.9–11 Recent articles have reviewed astrocyte functioning as intermediaries between neurons and cerebral blood vessels to adjust cerebral blood flow to neuronal activity.3,7,8 Potential astrocyte-derived vasoactive mediators of cerebrovascular responses include eicosanoids12,13 K$^+$,14,15 and ATP16, which appear to perform in concert.8

The principle excitatory cerebral neurotransmitter is glutamate that dilates cerebral arterioles to match blood flow to neural activity. Specific cells and mechanisms involved in coupling the glutamate release to arteriolar smooth muscle relaxation are uncertain. Astrocytes are uniquely positioned for sensing neuronal activity and regulating cerebral blood flow.7,8,17–19 They possess both metabotropic glutamate receptors (mGlurRs) and ionotropic glutamate receptors (iGlurRs). Glutamate stimulation of astrocytic mGlurR and iGlurR produces intracellular Ca$^{2+}$ oscillations and localized and global elevations of astrocyte intracellular Ca$^{2+}$ concentration ([Ca$^{2+}$]i).20–24 In brain slices, glutamate elevates astrocyte [Ca$^{2+}$], but reduces adjacent vascular smooth muscle cell [Ca$^{2+}$], that produces vasodilation.22,25 However, the signaling mechanisms between astrocytes and vascular smooth muscle that result in this dilation to glutamate remain uncertain with eicosanoids,17,25 K$^+$,14,15 and Ca$^{2+}$24 among the mechanisms considered.

CO could be a glutamate-induced, diffusible messenger used by astrocytes to signal for arteriole dilation. This hypothesis is rational because glutamatergic dilation of newborn pig cerebral arterioles, in vivo, is blocked by inhibition of HO that produces CO.26,27 Furthermore, astrocyte injury, in vivo, blocks piglet pial arteriolar dilation to glutamate making it reasonable to propose that astrocytes are the source of vasoregulatory CO involved in excitatory amino acid–induced cerebral vasodilation. CO dilates cerebral arterioles...
by activating smooth muscle cell large conductance Ca\(^{2+}\)-
activated potassium channels (K\(_{Ca}\) channels).\(^{28,29}\) Therefore,
we investigated whether astrocyte-derived CO increases
smooth muscle cell K\(_{Ca}\) channel activity, providing a mecha-
nism by which glutamate can cause arteriole dilation.
Specifically, the present study tested the hypothesis that
 glutamate stimulates astrocyte production of CO that in-
creases arteriole smooth muscle cell K\(_{Ca}\) currents, leading to
a decrease in intracellular Ca\(^{2+}\) ([Ca\(^{2+}\)]\(_i\)) and vasodilation.

Materials and Methods

Piglet Cerebral Arteriole Smooth Muscle
Cell Isolation

Procedures were approved by the University of Tennessee Health
Science Center Animal Care and Use Committee. Newborn pigs (1
to 3 days old, 1 to 2.5 kg; Nichol's Hog Farm, Olive Branch, Miss)
were anesthetized with ketamine hydrochloride (33 mg/kg im) and
acepromazine (3.3 mg/kg im). The brain was removed and placed
into ice-cold HEPES-buffered physiological saline solution (PSS).
For electrophysiological studies, arterioles (50 to 200 \(\umu\)m in diam-
eter) were dissected from the cerebral cortical surface. Individual
vascular smooth muscle cells were enzymatically dissociated from
cerebral arterioles using a procedure previously described.\(^{30}\)

Astrocyte Culture

Piglets were anesthetized as above, and adult HO-2\(^{-/-}\) and HO-2\(^{+/+}\)
mice were killed by peritoneal injection of sodium pentobarbital (130
mg/kg). Mouse procedures were approved by New York Medical
College Animal Care and Use Committee. Brains were removed and
placed in ice-cold DMEM with antibiotic/antimycotic (100 U/mL
penicillin, 100 mg/mL streptomycin, and 2.5 mg/mL amphotericin
B). Astrocytes were isolated, grown, and identified as described previously.\(^3\) Primary culture astrocytes were dislodged by trypsin-
EDTA and either transferred to DMSO (10%)/FBS (90%) and frozen
in liquid nitrogen for future use or directly plated on glass cover slips
(100 nmol/L).

Astrocyte Culture on Cytodex Microcarrier Beads

Confluent mouse HO-2\(^{-/-}\) and HO-2\(^{+/+}\) astrocytes were dislodged
with trypsin/EDTA and mixed with Cytodex microcarrier beads
(175 \(\umu\)m diameter, denatured collagen chemically coupled to a
matrix of cross-linked dextran, GE Healthcare), transferred into
spinner flasks and stirred intermittently (20 rpm 30 minutes on and
3 hours off) at 37°C and 5% CO\(_2\) in air. After 12 hours, the beads
were stirred continuously (20 rpm) for 4 to 6 days before experi-
ments. Cell density was approximately 10\(^6\) cells/mL beads.

Patch-Clamp Electrophysiology

A glass coverslip with or without a confluent layer of astrocytes was
placed in an experimental chamber. Freshly isolated cerebral arte-
riole smooth muscle cells were added to the chamber and allowed
to settle for 10 minutes. Potassium currents were measured by using the
whole cell perforated-patch-clamp configuration.\(^{28}\) Transient K\(_{Ca}\)
currents were measured at a steady membrane potential of \(-40\) mV
and calculated from \(\geq 5\) minutes of continuous gap-free data. At \(-40\)
mV, a transient K\(_{Ca}\) current was defined as the simultaneous opening
of 3 K\(_{Ca}\) channels. Single K\(_{Ca}\) channel currents were recorded at a
steady membrane potential of 0 mV in the presence of tachysagrin
(100 nmol/L).

CO Measurement

After overnight incubation in L-glutamine and serum-free DMEM,
astrocytes grown on Cytodex microcarrier beads (1 mL beads diluted
to 1.7 mL with Krebs solution) were placed into amber vials with
\(^{13}\)C\(_2\)O (\(^{13}\)CO, ISOTEC) as the internal standard. After 1 hour
incubation at 37°C, 100 \(\mu\)L of head space gas was collected for CO
detection by gas chromatography/mass spectrometry as described
before.\(^{31,32}\)

Detection of HO-2 Expression

Proteins from Laemmli buffer solubilized samples were separated by
12% SDS PAGE, transferred to PVDF membranes and blocked with
10% BSA in PBS-Twice (0.1%). Immunoblotting was performed using
the following antibodies: primary 1:250 rabbit anti-mouse
HO-2 antibodies (Stressgen), secondary 1:5000 mouse anti-
mouse \(\alpha\)-actin (Sigma Aldrich), secondary 1:10 000 goat anti-mouse
IgG-HRP (Santa Cruz Biotechnology). The immunocomplexes were
visualized with ECL Plus Western blot detection reagent (GE
Healthcare) and quantified by digital densitometry using Gel-Pro
Analyzer software (Media Cybernetics).

Brain Slice Preparation, [Ca\(^{2+}\)], and Arteriolar
Diameter Measurements

Newborn pig brains were removed and placed in cold (4 to 8°C)
M199 with 10 mmol/L HEPES, and 10 mmol/L glucose, pH 7.37.
Tangential slices were cut (200 \(\umu\)m thick) from the cerebral cortical
surface and placed in M199. Diameters of cortical surface arterioles
were measured in bicarbonate-buffered PSS (21% O\(_2\), 5% CO\(_2\))
superfused (1.5 mL/min, 35°C) brain slices using an inverted
microscope, CCD camera, and edge detection software (IonWizard,
IonOptix). \([\text{Ca}^{2+}]_i\) was measured in cerebral arterioles of piglet brain
slices using fura-2 with a method published previously.\(^{33}\) The
cerebral arteriolar wall in the brain slice was selected for data
acquisition.

To selectively injure astrocytes, slices were incubated with L-2-
alpha aminoacidic acid (L-AAA, 2 mmol/L). We,\(^2\) and others,\(^10,11\)
have shown previously that L-AAA treatment in vivo produces
histological evidence of injury to the superficial glia limitans and
loss of astrocyte-dependent cerebrovascular responses without altering
responses in general. Control slices were incubated with D-AAA,
the inactive isomer.

Chemicals

Cr (III) mesoporphyrin IX chloride (CrMP) was purchased from
Frontier Scientific. Papain was purchased from Worthington Bio-
chemical. All other chemicals were obtained from Sigma Chemical
unless otherwise stated.

Statistical Analysis

Values are means \(\pm\) SEM. For comparisons among more than 2
groups, results were subjected to a 1-way ANOVA for repeated
measures with Tukey post hoc test to isolate differences between
groups. Student \(t\) tests were used for comparison between each 2
groups of paired or unpaired data, as appropriate. \(P<0.05\) was
considered significant.

Results

Cerebral arteriole smooth muscle cells were allowed to settle
either on astrocytes or empty coverslips before measurement of
whole cell currents. Using patch-clamp electrophysiology, transient K\(_{Ca}\) current frequency and K\(_{Ca}\) channel activity were
recorded in smooth muscle cells. At \(-40\) mV, a physiological
membrane potential, glutamate (20 \(\umu\)mol/L) reversibly increased \((\approx 75\%)\) transient K\(_{Ca}\) current frequency in cerebral
arteriole smooth muscle cells that were in contact with
astrocytes (Figure 1). Conversely, glutamate had no effect on the
transient K\(_{Ca}\) current frequency of smooth muscle cells
that were not in contact with astrocytes (Figure 1).

Transient K\(_{Ca}\) current amplitudes are not normally distrib-
uted (failed Kolmogorov and Smirnov for a Gaussian distri-
bution at \( P<0.0001 \)). Therefore, transient \( \text{K}_{\text{Ca}} \) currents were divided into groups that are logical based on numbers of simultaneous channel openings (Table): small transient \( \text{K}_{\text{Ca}} \) currents (3 to 7 channel openings [1 channel=2.8pA\(^{\pm}\)]), midsized transient \( \text{K}_{\text{Ca}} \) currents (8 to 14 channel openings), and large transient \( \text{K}_{\text{Ca}} \) currents (15 to 30 channel openings).

As can be seen in the Table, the distribution is skewed toward smaller transient \( \text{K}_{\text{Ca}} \) currents, then medium sized transient \( \text{K}_{\text{Ca}} \) currents, and fewer large transient \( \text{K}_{\text{Ca}} \) currents. Glutamate increased the number of small (1.6-fold), medium (1.7-fold), and large (3.1-fold) transient outward currents in smooth muscle cells in contact with astrocytes, but did not change the number of outward currents of any amplitude in smooth muscle cells that were alone.

To investigate \( \text{K}_{\text{Ca}} \) channel regulation by glutamate, transient \( \text{K}_{\text{Ca}} \) currents were inhibited by depleting SR \( \text{Ca}^{2+} \) with thapsigargin (100nmol/L), a SR \( \text{Ca}^{2+} \) ATPase inhibitor that blocks \( \text{Ca}^{2+} \) sparks. Glutamate increased (\( \approx 65\% \)) single \( \text{K}_{\text{Ca}} \) channel activity when smooth muscle cells were in contact with astrocytes (Figure 2). In contrast, glutamate did not change \( \text{K}_{\text{Ca}} \) channel activity in smooth muscle cells without astrocytes.

To investigate the contribution of astrocyte HO to the responses, astrocytes were pretreated with the HO inhibitor CrMP (20\( \mu \)mol/L, 1 hour). Coverslips with CrMP-treated astrocytes were rinsed and then added to the recording chamber to avoid exposure of smooth muscle cells to the HO inhibitor. Cerebral arteriole smooth muscle cells were allowed to settle on CrMP-treated astrocytes. In contrast to the effect of glutamate on vascular smooth muscle cells in contact with untreated astrocytes, where transient \( \text{K}_{\text{Ca}} \) current frequency increased \( \approx 75\% \) and single \( \text{K}_{\text{Ca}} \) channel open probability increased \( \approx 65\% \), glutamate changed neither transient \( \text{K}_{\text{Ca}} \) current frequency nor \( \text{K}_{\text{Ca}} \) channel activity of smooth muscle cells in contact with CrMP-pretreated astrocytes (Figure 3).

Table. Effect of Glutamate on Piglet Cerebral Arteriole Smooth Muscle Cell (SMC) Transient \( \text{K}_{\text{Ca}} \) Currents

<table>
<thead>
<tr>
<th>Amplitude Range</th>
<th>SMC With Astrocytes</th>
<th>SMC Alone</th>
</tr>
</thead>
<tbody>
<tr>
<td>7–20pA</td>
<td>Control: 70±4</td>
<td>Glutamate: 61±6</td>
</tr>
<tr>
<td>21–40pA</td>
<td>Control: 41±3</td>
<td>Glutamate: 45±3</td>
</tr>
<tr>
<td>&gt;40pA</td>
<td>Control: 6±1</td>
<td>Glutamate: 19±2*</td>
</tr>
</tbody>
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Mean±SEM currents per cell in 10 minutes. n=7 cells with and without astrocytes.

\( ^*P<0.05 \) compared to control.

Figure 1. Glutamate (20\( \mu \)mol/L) elevates transient \( \text{K}_{\text{Ca}} \) current frequency in cerebrovascular smooth muscle cells in contact with astrocytes (A) but not in cerebrovascular smooth muscle cells alone (B). Summarized data are shown in C. n=7 and n=12 for smooth muscle cells alone and with astrocytes, respectively. \( ^*P<0.05 \) compared with zero.

Figure 2. Glutamate (20\( \mu \)mol/L) activates \( \text{K}_{\text{Ca}} \) channels in cerebrovascular smooth muscle cells in contact with astrocytes (A) but not in cerebrovascular smooth muscle cells alone (B). Summarized data are shown in C. n=6 and n=13 for smooth muscle cells alone and with astrocytes, respectively. \( ^*P<0.05 \) compared with zero.

To investigate \( \text{K}_{\text{Ca}} \) channel regulation by glutamate, transient \( \text{K}_{\text{Ca}} \) current frequency was increased by depleting SR \( \text{Ca}^{2+} \) with thapsigargin (100nmol/L), a SR \( \text{Ca}^{2+} \) ATPase inhibitor that blocks \( \text{Ca}^{2+} \) sparks. Glutamate increased (\( \approx 65\% \)) single \( \text{K}_{\text{Ca}} \) channel activity when smooth muscle cells were in contact with astrocytes (Figure 2). In contrast, glutamate did not change \( \text{K}_{\text{Ca}} \) channel activity in smooth muscle cells without astrocytes.

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As an alternative approach for depression of astrocyte CO production, as well as for investigation of the HO subtype involved in glutamate-induced CO production, we used HO-2 knockout mice. Wild-type (HO-2+/+) homogenates showed strong expression of HO-2, whereas there was no detectable HO-2 protein expression in HO-2 knockout (HO-2−/−) mice (Figure 4A). Glutamate more than doubled CO production by HO-2+/+ astrocytes (Figure 4B). In contrast, glutamate had no effect on CO production by HO-2−/− astrocytes (Figure 4B).

To examine the effect of HO-2 expression on the ability of astrocytes to activate KCa channels in cerebral arterial smooth muscle cells, piglet cerebral arteriole smooth muscle cells were allowed to settle on either HO-2+/+ or HO-2−/− mouse astrocytes. Transient KCa current frequency and KCa channel activity were recorded. As was the case when using piglet astrocytes, glutamate elevated transient KCa current frequency (2.3-fold) as well as KCa channel activity (2-fold) in piglet smooth muscle cells in contact with HO-2+/+ mouse astrocytes (Figure 5). In contrast, glutamate did not alter transient KCa current frequency or KCa channel activity in piglet smooth muscle cells in contact with HO-2−/− astrocytes (Figure 5).

We used newborn pig cerebral cortex slices to examine contributions of HO and astrocytes to glutamate regulation of arteriolar [Ca2+]i and diameter in structurally intact brain. Glutamate (30 μmol/L) decreased the fura-2 ratio (340/380 nm) in arterioles, indicating a decrease of [Ca2+]i (Figure 6). Pretreatment of slices with CrMP markedly inhibited the effect of glutamate on [Ca2+]i. In addition, glutamate dilated piglet neocortical slice arterioles (from 111±10 to 123±11 μm; Figure 7). In contrast, glutamate did not alter the diameters of arterioles in brain slices pretreated with CrMP, suggesting CO generated by HO is required for glutamate-induced vasodilation. CrMP-treated slice arterioles constricted normally to the thromboxane receptor agonist U46619 (data not shown). Paxilline, a selective KCa channel blocker, reversed glutamate-induced dilation, suggesting the dilation was mediated by KCa channels. Also, after treatment of brain slices with L-AAA (2 mmol/L, 2 hours), a selective astrocyte toxin, arterioles did not dilate to glutamate (Figure 7D). In contrast, arterioles within slices incubated with the inactive isomer, D-AAA, dilated similarly to glutamate as did arterioles in untreated slices. L-AAA did not depress overall arteriolar reactivity as indicated by similar dilations to sodium nitroprusside of arterioles in L-AAA.
and D-AAA (15%) treated slices. These data show that astrocytes, HO-2, and KCa channels are required for glutamate-induced cerebral arteriolar dilation in newborn pigs.

**Discussion**

Major findings of the present study are that: (1) Glutamate activates transient KCa currents and KCa channel activity in cerebral arteriolar smooth muscle cells that are in contact with astrocytes but not in smooth muscle cells alone; (2) Glutamate increases CO production by intact astrocytes but not by genetically HO-2 deficient astrocytes; (3) Pharmacological inhibition of HO or genetic ablation of astrocyte HO-2 eliminates glutamate-induced KCa channel activation in cerebral arteriolar smooth muscle cells in contact with these astrocytes; (4) Glutamate decreases brain slice arteriolar smooth muscle [Ca^{2+}], through a mechanism that is attenuated by pharmacological inhibition of HO; and (5) Glutamate-induced dilation of piglet neocortical brain slice arterioles is blocked by either HO inhibition, KCa channel inhibition, or astrocyte injury.

Between the present and a recent study, we use 3 approaches, isolated cells, brain slices, and cranial windows in vivo. Each has different strengths and weaknesses and the combination is mutually complimentary. Brain slices have no descending pressure or blood flow. But slices allow arteriole wall [Ca^{2+}], measurements and remove both neuronal influences from beyond the study area and blood borne mediators. The results from slices mirror the in vivo experiments that show glutamate causes arteriolar dilation and brain CO production which are inhibited by astrocyte injury. In vivo, arterioles have normal pressure and flow and CO production can be measured, but specific cell types involved in communication or CO production, channels involved, and [Ca^{2+}], measurements are not possible. Isolated cells allow specific communication between myocytes and astrocytes to be investigated, inhibitor treatment of only astrocytes, using HO-2
knockout astrocytes with wild-type arteriolar smooth muscle, and measurement of CO production specifically by astrocytes. Thus, the combined 3 approaches lead to a more complete picture of the functional control mechanisms.

CO is produced physiologically by catabolism of heme to CO, iron, and biliverdin. HO catalyzes this reaction with oxidation of NADPH. HO is expressed as 3 known isoforms: HO-1, HO-2, and a third isoform (HO-3) with much lower oxidation of NADPH. HO is expressed as 3 known isoforms: HO-1, HO-2, and a third isoform (HO-3) with much lower heme degrading activity and expression.37 The present study shows that glutamate increases CO production by HO-2+/+ mouse astrocytes but not HO-2-/- astrocytes that do not express HO-2. CO reduces vascular smooth muscle tone both in vitro38,39 and in vivo.37,40 Indications of the functional significance of CO are supported by alterations of responses to important physiological cerebrovascular regulatory stimuli on HO inhibition. In the newborn pig in vivo, pial arteriolar dilations to glutamate, hypotension, and hypoxia are inhibited after topical treatment with CrMP that blocks CO production.26,41

Although CO has been demonstrated to increase transient K_{c_{a}} currents when applied directly to isolated vascular smooth muscle cells or arterioles, the present study is the first to show that a HO-2 product produced by another cell, an astrocyte, can activate transient K_{c_{a}} currents in an associated arteriolar smooth muscle cell. Because HO products other than CO do not activate K_{c_{a}} channels,28 the HO-2 product activating the K_{c_{a}} channel must be CO. Of additional significance, the signal, glutamate, is a primary mediator of brain function that does not directly affect K_{c_{a}} currents in cerebrovascular myocytes (Figure 1). The signal from astrocytes is necessary to provide the functional hyperemic response.

Our studies using cranial windows in vivo, found that either astrocyte injury or inhibition of CO production blocks dilation of newborn pig pial arterioles to topical glutamate application.9,26 In the present study, we show that in the absence of astrocytes or with astrocytes pretreated with CrMP, glutamate does not increase either smooth muscle cell transient K_{c_{a}} currents or K_{c_{a}} channel activity. To confirm that HO-2 is involved in this signaling pathway, piglet smooth muscle cells were allowed to contact mouse HO-2+/+ and HO-2-/- astrocytes. Glutamate increased transient K_{c_{a}} currents as well as K_{c_{a}} channel activity of smooth muscle cells attached to HO-2+/+ astrocytes, but not those attached to HO-2-/- astrocytes. We show that glutamate-induced dilation of brain slice arterioles is abrogated by either blocking the enzyme that produces CO or by blocking the K_{c_{a}} channel that CO activates. Further, HO inhibition prevented glutamate-induced reduction of [Ca^{2+}] in brain slice arterioles. All these data are consistent with the hypothesis that glutamate stimulates astrocyte HO-2, producing the diffusible gasotransmitter, CO, which activates K_{c_{a}} channels in adjacent cerebral microvascular smooth muscle cells.

In contrast to rat hypothalamus and newborn pig cerebral cortex,26 the sole reported influence of the HO/CO system on vascular tone in adult rat cerebral cortex has been constriction.43 Endogenous CO appears to have a tonic inhibitory effect on NO production in rat cerebral cortex because the HO inhibitor, zinc protoporphrin (ZnPP) dilated pial arterioles over a 1-hour period, and enhanced cerebral NO production as estimated using diaminofluorescein-2.43 The dilation was blocked by L-NAME and by addition of CO to the superfusion solution. Conceivably, contributions of CO to cerebrovascular regulation could be biphasic with basal production providing tonic inhibition of NOS with resultant increased tone, whereas acute CO elevations in response to stimulation lead to dilation. Also, available data on responses of isolated adult cerebral arteries to CO suggest that species differences exist. Dilation to exogenous CO added to the bathing solution...
has not been detected in rabbit, rat, or mouse cerebral arteries in vitro.\textsuperscript{44,45} On the other hand, CO dilates dog basilar artery segments.\textsuperscript{46} In addition, in pigs, responses of pial arterioles to CO are age-dependent with juvenile pigs, and adult rats, having reduced dilations compared with baby pigs.\textsuperscript{47}

CO causes dilation by activating smooth muscle cell KC\textsubscript{a} channels.\textsuperscript{26-29,48} Absence of dilation of rat cerebral arterioles and arteries to CO in vitro (above) is surprising because CO dilates peripheral rat arterioles via KC\textsubscript{a} channel activation.\textsuperscript{49,50} In vascular smooth muscle cells, several KC\textsubscript{a} channels are activated by spatially localized intracellular Ca\textsuperscript{2+} transients, termed Ca\textsuperscript{2+} sparks, that elevate the local [Ca\textsuperscript{2+}]\textsubscript{i} into the micromolar range.\textsuperscript{51} Transient KC\textsubscript{a} currents induce membrane hyperpolarization that reduces voltage-dependent Ca\textsuperscript{2+} channel activity, and thus decreases global [Ca\textsuperscript{2+}]\textsubscript{i} producing dilation. CO increases transient KC\textsubscript{a} currents by enhancing the coupling of Ca\textsuperscript{2+} sparks to KC\textsubscript{a} channels.\textsuperscript{28} The KC\textsubscript{a} channel \(\alpha\)-subunit contains a heme-binding pocket and binding of heme inhibits KC\textsubscript{a} channel activity.\textsuperscript{52} CO, by binding to channel-bound heme, changes the association of heme with the KC\textsubscript{a} channel and causes activation.\textsuperscript{48} Therefore, the KC\textsubscript{a} channel is functionally a heme-protein, with heme acting as the binding site for CO.\textsuperscript{48}

Species or age differences exist in Ca\textsuperscript{2+} spark-to-KCa channel coupling efficiency that could influence arteriole smooth muscle sensitivity to CO and possibly even the role of CO in regulation of cerebrovascular circulation. In adult rat cerebrovascular smooth muscle cells, virtually all Ca\textsuperscript{2+} sparks produce transient KC\textsubscript{a} currents.\textsuperscript{53,54} Conversely, not all Ca\textsuperscript{2+} sparks produce transient KC\textsubscript{a} currents in either newborn pig\textsuperscript{28,55} or adult human\textsuperscript{56} cerebral arterioles. Therefore, the ability of CO to hyperpolarize and dilate rat cerebral arterioles may be less\textsuperscript{44} than in newborn pig cerebral arterioles because CO increases the coupling of Ca\textsuperscript{2+} sparks to KC\textsubscript{a} channels and rat Ca\textsuperscript{2+} spark-to-KCa channel coupling is essentially unitary at physiological membrane potentials.

In the present study, rather than report transient KC\textsubscript{a} current amplitude as the mean of all transient KC\textsubscript{a} currents, we divided transient KC\textsubscript{a} currents into smaller (7 to 20 pA), larger (21 to 40 pA), and largest (>40 pA) currents. As can be seen in Table, transient KC\textsubscript{a} current frequency in all size categories increased on treatment with glutamate. In piglets, smaller amplitude Ca\textsuperscript{2+} sparks do not cause transient KC\textsubscript{a} currents.\textsuperscript{28,34} CO increases the number of smaller amplitude transient KC\textsubscript{a} currents because smaller, uncoupled Ca\textsuperscript{2+} sparks become coupled to KC\textsubscript{a} channels.\textsuperscript{28} The addition of these smaller currents depresses the overall mean, which explains the minimal change in mean transient KC\textsubscript{a} current amplitude, even though large amplitude transient KC\textsubscript{a} currents are markedly increased. An accurate depiction of the effect of glutamate on transient KC\textsubscript{a} current amplitude requires accounting for the increased number of smaller currents. Glutamate increases frequencies of transient KC\textsubscript{a} currents across the amplitude spectrum because glutamate uses CO to increase Ca\textsuperscript{2+} spark-to-KCa channel coupling.

The present study shows glutamate increases CO production by astrocytes, but coupling mechanisms are not known. Stimulation of mGluR and mGluR increase Ca\textsuperscript{2+} oscillations in astrocytes,\textsuperscript{20-24} electrical field stimulation increases brain slice astrocyte endfoot [Ca\textsuperscript{2+}]\textsubscript{i} and inhibition of calmodulin blocks glutamate stimulation of CO production in cerebral microvessels and cortical neurons.\textsuperscript{57,58} Therefore, it is reasonable to speculate that glutamate stimulates CO production in astrocytes via elevation of astrocytic [Ca\textsuperscript{2+}]\textsubscript{i}. Increasing [Ca\textsuperscript{2+}]\textsubscript{i}, could increase HO-2 activity directly to elevate CO production or by a variety of indirect actions including delivery of electrons from NADPH via cytochrome P450 reductase, delivery of heme to HO-2, or activation of kinases that elevate HO-2 activity. Glutamate also could increase HO-2 activity via Ca\textsuperscript{2+}-independent kinase pathways. In endothelium, vascular smooth muscle, and neurons HO-2 activity can be increased by phosphorylation.\textsuperscript{31,58} mGluR elevates diacylglycerol that stimulates protein kinase C, which could phosphorylate and activate HO-2.

In summary, the present study indicates that the neurotransmitter glutamate activates transient KC\textsubscript{a} currents and KC\textsubscript{a} channel activity in newborn pig cerebral arteriole smooth muscle cells by increasing CO production by associated astrocytes. Either inhibition of CO production or treatment with astrocyte toxin prevents glutamate-induced arteriolar dilation in piglet brain slices. These data support the conclusion that astrocytes use CO as a diffusible messenger to cause cerebral arteriole dilation and enhance local blood flow to match increased glutamatergic neuronal activity.

Sources of Funding
This research was supported by NHLBI/NIH and NEI/NIH.

Disclosures
None.

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Circ Res. 2008;102:234-241; originally published online November 8, 2007; doi: 10.1161/CIRCRESAHA.107.164145

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7330. Online ISSN: 1524-4571

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