Spatial Features of Focal Infarction After Hydralazine Treatment in Stroke-Prone Spontaneously Hypertensive Rats

Peter Coyle, PhD, and Xiaobin Feng, MM

**Background and Purpose:** Rapid occlusion of the middle cerebral artery above the rhinal fissure produces a large ischemic infarct in hypertensive rats, but this occlusion results in a minimal lesion in young normotensive rats. Our purpose was to attenuate rising blood pressure in young stroke-prone spontaneously hypertensive rats with hydralazine before the occlusion to determine if the gross infarct volume is smaller, and if it is, to determine whether length, width, depth, or surface area of the infarct changes, which could suggest a mechanism of protection.

**Methods:** Untreated rats (*n*=6) and rats receiving hydralazine for 1.5 (*n*=6) or 5 (*n*=5) weeks were anesthetized, and the middle cerebral artery was rapidly occluded with a ligature. One day later the rats were killed and the brains were fixed in formalin. Fine-grain-release film that is sensitive to spectral properties of the infarct was used to photograph the tissue. Infarcted areas were traced on paper and then digitized for measurements and computations with a microcomputer.

**Results:** Compared with untreated rats, tail systolic blood pressure (120±3 versus 138±4 mm Hg), infarct volume (61±4 versus 93±6 mm$^3$), infarct surface area (39±1 versus 54±2 mm$^2$), infarct width (3.8±0.1 versus 4.8±0.2 mm), and infarct length (6.0±0.3 versus 8.1±0.3 mm) were less in rats receiving hydralazine for 5 weeks (*p*<0.05). No change was detected in infarct depth.

**Conclusions:** Treatment of young stroke-prone spontaneously hypertensive rats with hydralazine for 5 weeks before middle cerebral artery occlusion results in a smaller infarct. The narrower, shorter dimensions indicate increased protection against lateral enlargement of the infarct and the possibility that protection was due to increased collateral blood flow through modified blood vessels. *(Stroke 1993;24:253–258)*

**Key Words** • cerebral arteries • cerebral infarction • hydralazine • rats

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**Sudden,** permanent occlusion of the rat middle cerebral artery (MCA) above the rhinal fissure beyond the lenticulostriate arteries reduces blood flow to the distal MCA cortical territory.\(^1,2\) The reduced blood flow precedes a large cortical infarct in adult spontaneously hypertensive rats with chronic hypertension.\(^2-7\) In contrast, 5-week-old normotensive Wistar rats usually escape this lesion,\(^8-10\) whereas in adult normotensive rats the infarct is variable in frequency and size.\(^2,4,11,12\) In adult normotensive Wistar rats blood flow to the territory of the occluded MCA is reduced shortly after occlusion.\(^1,2\) After weeks of MCA occlusion arterial anastomoses leading to the MCA territory have wider lumens,\(^13,14\) blood flow is normal, and blood flow reserve is restored in normotensive Wistar rats protected from infarction.\(^3\) We conjecture that in young spontaneously hypertensive rats the continued rising blood pressure (BP)\(^15\) produces vascular wall structural changes\(^16,17\) that reduce the blood flow reserve\(^18\) of collateral anastomoses, thus increasing the risk of infarction after sudden occlusion of the MCA. Our objective was to study the effect of MCA occlusion on cortical infarction in young stroke-prone spontaneously hypertensive rats (SHRSP) before fully developed vascular wall changes become present during the established stage of hypertension (systolic BP of >150 mm Hg). Because young normotensive Wistar rats usually escape this lesion after MCA occlusion,\(^8-10\) they were not included in this study. Our first goal was to determine whether gross infarct volume was smaller in young SHRSP after attenuating the rise in BP with hydralazine before MCA occlusion. If volume is smaller, our second goal was to examine infarct length, width, and depth to see where significant change occurs because the place of protection may signify a mechanism of protection.

**Materials and Methods**

Group I rats (*n*=6, weight 64±3 g) drank tap water without hydralazine before occlusion of the MCA at 6 weeks of age. Group II rats (*n*=6, weight 101±14 g) received hydralazine (50 mg/500 ml tap water, changed daily) in their drinking water ad libitum for 1.5 weeks.

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before MCA occlusion at 7 weeks of age. Group III rats 
\( n=5 \), weight 113±18 g) were treated with hydralazine 
ad libitum (same as group II) for 5 weeks before MCA 
occlusion at 9 weeks of age. Each group of rats was 
obtained from two or more inbred litters and fed 
standard rat chow. Two litters provided animals for both 
group II and group III. Both sexes were present in all 
groups.

Five to seven tail systolic BP recordings were ob-
tained for each animal following procedures detailed 
previously.\(^8\) The last three recordings were averaged 
to yield one BP value for each rat. BP readings were 
obtained 0–2 days before and on the day after MCA 
occlusion.

All rats were anesthetized with 132 mg/kg i.m. keta-
mine hydrochloride. Details are given elsewhere\(^8\) of 
surgery necessary to expose the right MCA above the 
rhinal fissure beyond the origins of the lenticulostrate 
arteries supplying subcortical structures. A 2-mm-diam-
eter craniectomy was drilled with a \#6 dental burr 
about 1 mm rostral and 2 mm dorsal to the rostral fusion 
point of the zygomatic and squamous bones. Monofil-
mament nylon thread, about 35 μm in diameter, was used 
to ligate the MCA. The occlusion was about 1,700 μm 
dorsal to the rhinal fissure and 300–500 μm ventral to 
the MCA bifurcations distributing to the frontal, pari-
etal, and occipital cortical regions. The rats were not 
paralyzed, no mechanical ventilation was used, and no 
respiratory gases were administered. After wound clo-
csure with sutures, postsurgical care followed procedures 
previously outlined.\(^8\)

On the day after MCA occlusion, the rats were 
anesthetized with ether and then injected with 40–50 
mg/kg i.v. papaverine hydrochloride to produce maxi-
mal vasodilation and death. Tissue fixation was initiated 
by perfusion with 50 ml of 10% neutral buffered forma-
lin into the thoracic aorta occluded at the diaphragm 
with a hemostat. The brains were removed and stored in 
fixative for 9 months. Photographic differentiation of 
the infarct was achieved with fine-grain-release film that 
is highly sensitive to the spectral properties of infarcted 
tissue (Figure 1).

The brains were placed in a custom-made holder to 
photograph the hemisphere at a 45° angle to the mid-
sagittal plane. This orientation showed the cortical 
surface of the infarct in one image (Figure 1A). At ×14 magnification coordinates of the infarct border were 
digitized, and infarct area at the pial surface was 
calculated using Sigma-Scan (Jandel Scientific, San Ra-
fael, Calif.). The maximum length of the infarct was in 
the direction of the long axis of the brain. Length was 
measured at 0.25-mm intervals parallel to the maximum 
dimension and averaged to one value for each rat. 
Width was measured at 0.25-mm intervals perpendicu-
lar to the length measurement and averaged to one 
value for each rat.

All brains were cut in the coronal plane using an 
Activational Systems, Inc. model RBM-4000C holder 
(Warren, Mich.) to control section thickness at 1 mm. 
Sections were photographed, and infarct borders were 
traced from negatives projected at ×14 magnification. 
Tracings were made without observer knowledge of the 
treatment group. Infarct borders were digitized and 
areas computed. Infarct volume for each coronal section 
was obtained by averaging the surface area of panne-
Coyle and Feng  Focal Infarction  255

**FIGURE 1.** Photomicrographs. Panel A: View of stroke-prone spontaneously hypertensive rat (SHRSP) brain rotated 45° to midsagittal plane. Arrow indicates site where middle cerebral artery (MCA) was occluded. Brain from rat receiving hydralazine for 5 weeks before MCA occlusion and fixation in formalin. Magnification same as in Panel B. Panel B: View of coronal section of untreated SHRSP brain 1 day after MCA occlusion and fixation in formalin.

clusion. Second, the narrower, shorter dimensions of small infarcts reveal protection against lateral (side and end) enlargement of the infarct that may result from blood flow from lateral sources. Third, the similar depths of small and large infarcts is evidence that minimal, if any, protection occurred on the underside of the cortical infarct, which lacks a deeper source of collateral blood supply.

Others have demonstrated smaller infarcts after MCA occlusion in adult SHRSP following reductions in BP with hydralazine and hydrochlorothiazide or with cilazapril for 3 months, and after hydralazine treatment for 10 weeks in spontaneously hypertensive rats (SHR) infarcts were smaller. We found that 1.5 weeks of hydralazine treatment in combination with ketamine anesthesia was no more protective than ketamine alone, which is evidence that the interaction of the two drugs produced minimal, if any, tissue protection. With hydralazine treatment for 5 weeks, the smaller infarct confirms the finding that hydralazine requires a temporal component to produce some tissue protection. That tissue protection requiring a temporal component was probably independent of an effect of ketamine used in this study or of halothane used in the earlier study.

Concerning effects of anesthesia used during MCA occlusion, ketamine hydrochloride, an N-methyl-D-aspartate (NMDA) antagonist, produced no more tissue protection than halothane in adult SHR. In adult SHRSP anesthetized with sodium pentobarbital, infarct volume was not significantly different from that in adult SHR anesthetized with halothane (p > 0.05 for reported means±SEM). The data suggest that differences in tissue protection produced by acute administration of halothane, sodium pentobarbital, or ketamine...
TABLE 1. Parameters of Infarct After Middle Cerebral Artery Occlusion in Stroke-Prone Spontaneously Hypertensive Rats

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Untreated (n=6)</th>
<th>1.5 weeks (n=6)</th>
<th>5 weeks (n=5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (mm³)</td>
<td>92.7±6.3</td>
<td>93.8±5.4</td>
<td>61.2±3.8†</td>
</tr>
<tr>
<td>Pial surface area (mm²)</td>
<td>53.5±2.4</td>
<td>47.5±1.8</td>
<td>38.5±1.4*†</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>4.8±0.2</td>
<td>4.6±0.2</td>
<td>3.8±0.1*†</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>8.1±0.3‡</td>
<td>7.3±0.4‡</td>
<td>6.0±0.3*‡</td>
</tr>
<tr>
<td>Coronal section</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (mm)</td>
<td>1.9±0.1‡</td>
<td>2.1±0.1‡</td>
<td>2.0±0.0‡</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>4.7±0.2</td>
<td>4.6±0.2</td>
<td>3.6±0.2*†</td>
</tr>
<tr>
<td>Superficial (mm)</td>
<td>5.6±0.3§</td>
<td>5.6±0.3§</td>
<td>4.2±0.3*‡§</td>
</tr>
<tr>
<td>Deep (mm)</td>
<td>3.8±0.1</td>
<td>3.6±0.1</td>
<td>2.9±0.1*‡</td>
</tr>
</tbody>
</table>

Values are mean±SEM.
* p<0.05 versus untreated.
† p<0.05 versus hydralazine at 1.5 weeks.
‡ p<0.05 versus width.
§ p<0.05 versus deep.

are minimal in spontaneously hypertensive rat strains with MCA occlusion. Furthermore, a single dose (5 mg/kg) of MK-801, a noncompetitive NMDA antagonist, provided no significant tissue protection after MCA occlusion in adult SHR anesthetized with halothane.20 A single dose (1 mg/kg) of MK-801 before MCA occlusion had a small but significant protective effect in 8-week-old SHR anesthetized with ketamine,13 which suggests that a single dose of ketamine was appreciably less effective on NMDA-mediated protection or that MK-801 protected through a mechanism different from that of ketamine. While the possibility was not ruled out that ketamine produced some protection in both control and experimental groups, the protection was probably minimal.

As early as 15 days after birth, BP is elevated in SHR compared with normotensive rats, and medial hypertrophy is evident in cerebral vascular beds at this very early age.21 Protection against infarction could depend upon reversal or attenuation of vascular structural changes that are produced secondary to increased systolic BP,15 elevated pulse pressure,22 or even changes unrelated to high BP.9,15 Reversal of medial hypertrophy,16-18,21,23 recovery from endothelial dysfunction,24 and prevention or reversal of "remodeling" of vessels into smaller vessels27 all require time, and complete normalization may never occur after BP reduction. Furthermore, the hypotensive action of hydralazine could reduce perfusion downstream to fully dilated but structurally narrowed anastomoses,13,14,25 thereby making flow pressure dependent in collateral-dependent tissue.26 Thus, the amount and location of tissue protected by hydralazine after MCA occlusion in SHRSP is probably determined more by flow reserve in the anastomoses and downstream driving pressure within cortical penetrating arterioles than by NMDA receptor blockade from ketamine.

Narrower, shorter, wedge-shaped gross infarcts were indicative of increased tissue protection in a circumferential region surrounding the infarct. This region of increased protection was located closer to pial surface MCA anastomoses with branches of the anterior and posterior cerebral arteries than to the infarct center. Others27-29 have demonstrated a gradient of blood flow that increases with distance from the site of MCA occlusion, which suggests that increased tissue protection was obtained from increased blood flow in cortical penetrating arterioles30 that frequently course parallel to the edge of the wedge-shaped infarct (Figure 1B).

In contrast to the narrower, shorter dimensions of smaller cortical infarcts, we found cortical infarct depth to be similar in large and small lesions. Protection was not observed on the underside of the lesion, possibly because no deep collateral blood supply exists there. However, others2,29,31 have demonstrated that infarcted cortex is thicker due to edema and swelling, which is likely to alter perfusion hemodynamics and obscure normal from injured or infarcted tissue. Thus, we do not

**FIGURE 2.** Bar graphs showing effect of 5 weeks of hydralazine treatment (nearly 25 mg/kg/day ad libitum) on brain infarct volume and, as viewed on pial surface, infarct length, width, and surface area in stroke-prone spontaneously hypertensive rats (SHRSP, n=5) compared with untreated SHRSP (n=6). *p<0.05 versus untreated.
exclude the possibility that any real difference within the core of the infarct may have been obscured.

In summary, antihypertensive treatment of young SHRSP with hydralazine for 5 weeks before rapid occlusion of the MCA results in a smaller core infarct than in untreated SHRSP. Spatial features of the smaller, focal infarct indicate that protection is increased laterally and possibly that protection is due to greater blood flow through modified anastomotic blood vessels.

References


Editorial Comment

Occlusion of the middle cerebral artery produces a marked decrease in blood flow and a large infarct in experimental models of chronic hypertension.1,2 In contrast, similar arterial occlusion in normotensive control animals produces little or no infarction.

After chronic hypertension has been established, antihypertensive therapy decreases infarct volume in spontaneously hypertensive rats in response to focal cerebral ischemia.3,4 The magnitude of this protective effect is dependent on the duration of treatment.5 The present study by Coyle and Feng suggest that early treatment of stroke-prone spontaneously hypertensive rats with hydralazine, which essentially prevents the development of hypertension, also protects against brain damage following occlusion of the middle cerebral artery. Protection against infarction may be due to increased blood flow through collateral vessels.

The mechanism by which antihypertensive treatment protects cerebral blood vessels is not fully defined but may include 1) prevention or reversal of structural changes in cerebral arterioles, 2) maintenance or restoration of normal endothelium-dependent responses, and 3) improvement in cerebral blood flow reserve (minimal vascular resistance) and collateral vascular capacity.6–7

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