Cerebral Vasoconstrictor Responses to Serotonin After Dietary Treatment of Atherosclerosis: Implications for Transient Ischemic Attacks

Donald D. Heistad, MD, Keith Breese, and Mark L. Armstrong, MD

Serotonin, which is released when platelets aggregate at carotid lesions, may contribute to cerebral ischemia. Our goal was to test the hypothesis that dietary treatment of atherosclerosis reverses the augmented cerebral vasoconstrictor response to serotonin. We studied normal cynomolgus monkeys, atherosclerotic monkeys, and atherosclerotic monkeys that were fed a normal (regression) diet for 18 months. Morphometric studies indicated that the regression diet reduced intimal area in the carotid arteries by about 50–75%. Cerebral blood flow was measured with microspheres, and microvascular pressure was measured with a micropipette in pial arteries that were approximately 300 μm in diameter. Values for cerebral blood flow and arteriolar pressure were used to calculate resistance of large cerebral arteries (>300 μm diameter). Infusion of serotonin produced a modest increase in the resistance of large cerebral arteries in normal monkeys. Vasoconstrictor responses to serotonin were increased more than fivefold in atherosclerotic monkeys. The major finding of the study is that dietary treatment of atherosclerosis abolishes augmented cerebral responses to serotonin. (Stroke 1987; 18:1068-1073)

Large arteries as well as arterioles play an important role in the regulation of cerebral blood flow (CBF). Hypercholesterolemia in nonhuman primates produces atherosclerotic lesions in large extracranial arteries with relative sparing of intracranial arteries including extraparenchymal vessels. We have observed that diet-induced atherosclerosis in primates impairs cerebral vasodilator responses and potentiates vasoconstrictor responses to serotonin. Transient ischemic attacks (TIAs) usually are produced by platelet adhesion, aggregation, and embolization from plaques in large extracranial arteries. Platelets contain large amounts of serotonin. Release of serotonin during the aggregation of platelets, coupled with augmented responses to serotonin in atherosclerotic arteries, may produce pronounced vasoconstriction and contribute to focal cerebral ischemia.

Dietary treatment of atherosclerosis in primates results in reduction of lesion size. Although the intima remains thickened compared with normal vessels, cerebral vasodilator responses to hypercapnia are improved significantly. It is not known whether dietary treatment of atherosclerosis reduces the hyperresponsiveness of cerebral vessels to constrictor stimuli.

The goal of this study was to test the hypothesis that dietary treatment of atherosclerosis in primates reduces the hyperresponsiveness of cerebral vessels to serotonin.

Materials and Methods

Three groups of male cynomolgus monkeys were studied. Seven normal monkeys were fed commercial laboratory chow (Purina Monkey Chow, Ralston Purina Co., Richmond, Ind.) (normal group). Eight monkeys were fed an atherogenic diet, which contained 41% of total calories as fat and 0.8% cholesterol, for 18–20 months (atherosclerotic group). Eight monkeys were fed the same atherogenic diet for 18 months and then were fed commercial laboratory chow for 18–20 months (regression group). The monkeys weighed 5.9±0.2 kg (mean±SEM). At intervals of 3–4 months, the monkeys were sedated with 10 mg/kg i.m. ketamine HCl and venous blood samples were obtained. Total cholesterol and triglycerides were determined with the protocol used by the Lipid Research Clinics for the Autoanalyzer II (Technicon Instruments, Inc., Tarrytown, N.Y.). At the time of study, the monkeys were sedated with 12 mg/kg i.m. ketamine and anesthetized with 75–100 mg/kg i.v. chloralose. The monkeys were intubated and ventilated with room air and supplemental oxygen. When variability of arterial pressure or heart rate increased, supplemental doses of chloralose were injected. The monkeys usually required 50 mg/kg i.v. after completion of surgery (about 4 hours after induction of anesthesia) and 50 mg/kg 1–2 hours later. Rectal temperature was maintained at 37–38°C with a heating pad.

A catheter was inserted through a femoral artery to the descending aorta to measure aortic pressure and to obtain blood samples. Catheters were inserted into

From the Department of Internal Medicine, Veterans Administration Medical Center and Cardiovascular Center, University of Iowa College of Medicine, Iowa City, Iowa.

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Address for correspondence: Donald D. Heistad, MD, Department of Internal Medicine, University of Iowa College of Medicine, Iowa City, IA 52242.

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Measurement of Pial Artery Pressure and Cerebral Blood Flow

We have described these methods in detail previously.6,13 Pial artery pressure and diameter were measured in an open-skull preparation. A craniotomy was performed over the left parietal cortex. A wax dam was built around the cranial window and supported with dental acrylic. The dura was opened with a needle, resected with ophthalmic scissors, and superfused with artificial cerebrospinal fluid (CSF).

Artificial CSF was prepared as described previously.9 This solution was aerated with 5% CO₂ and 95% N₂ and infused through the inlet port at 3–5 ml/min to superfuse the dural opening. We measured pial artery pressure with a micropipette that had a sharp beveled tip 3–6 μm in diameter. The micropipette was filled with 1.5 M NaCl solution, and pressure was measured with a servo-null device (Model 4A, Instruments for Physiology and Medicine, Inc., San Diego, Calif.). The micropipette was lowered into the pool of CSF with a micromanipulator, the micropipette was balanced, and a zero value was established. The micropipette then was inserted into the lumen of a pial artery. Pressure was measured in pial arteries of 285 ± 51 μm diameter in normal monkeys, 280 ± 50 μm diameter in atherosclerotic monkeys, and 291 ± 35 μm diameter in regression monkeys (difference not significant). Diameter of pial arteries was measured with an electronic micrometer (Model 142A, ITP, Inc., Sunnyvale, Calif.), a television camera mounted on a Leitz compound microscope (Rockleigh, N.J.), and a video monitor.

Microspheres (15 μm mean diameter) labelled with ⁴⁴Sc, ⁵⁸Sr, ⁶⁴Nb, ⁹⁵Sn, ¹⁴¹Ce, and ¹⁵³Gd (New England Nuclear, Boston, Mass.) were used to measure CBF. Microspheres were injected into the left atrium in 15 seconds. Reference blood samples were withdrawn from the brachial arteries during the 10 seconds before injection until 2 minutes after injection of the microspheres. The monkey was killed with i.v. KCl at the end of the experiment. The ipsilateral cerebrum was removed, tissue and blood samples were weighed and counted in a gamma counter, and nuclide separation was accomplished with standard methods.

CBF was calculated as CBF = [(counts/g brain × 100 × withdrawal rate of reference blood samples) / counts in reference blood samples]. Large artery resistance (LAR) was calculated as LAR = [(aortic pressure – pial artery pressure)/CBF].

Experimental Protocol

Pial artery pressure and CBF were measured during a control period, during infusion of serotonin into the left atrium, during a second control period, and during systemic hypocapnia. We infused 8 and 40 μg/kg/min serotonin into the left atrium. Hypocapnia was produced by increasing the rate and tidal volume of the respirator. Serotonin and hypocapnia tended to reduce arterial pressure in several normal and regression monkeys, and a ligature around the descending aorta was tightened to keep arterial pressure in the upper half of the body from falling. Serotonin tended to increase arterial pressure in several atherosclerotic monkeys, and blood was removed during infusion of serotonin in these monkeys to prevent this increase in arterial pressure.

Serotonin was infused for about 3 minutes before microspheres were injected, and the infusions were continued for about 2 minutes after injection of microspheres. Hypocapnia was maintained for about 15 minutes before microspheres were injected. We waited for at least 15 minutes between interventions.

In normal monkeys, Paco₂ was 39 ± 0.5 mm Hg, Po₂ was 106 ± 7 mm Hg, and pH was 7.41 ± 0.01 during control, and, except during hypocapnia, these values did not change significantly. During hypocapnia, Pco₂ decreased to 16 ± 0.9 mm Hg and pH increased to 7.67 ± 0.05. In atherosclerotic monkeys, Paco₂ was 38 ± 0.2 mm Hg, Po₂ was 105 ± 3 mm Hg, and pH was 7.43 ± 0.01 during control conditions; Pco₂ decreased to 18 ± 0.6 mm Hg and pH increased to 7.61 ± 0.03 during hypocapnia. In regression monkeys, Paco₂ was 38 ± 0.6 mm Hg, Po₂ was 106 ± 7 mm Hg, and pH was 7.44 ± 0.02; Pco₂ decreased to 18 ± 0.7 mm Hg and pH increased to 7.63 ± 0.02 during hypocapnia. Control values for artificial CSF in all 3 groups were maintained at levels close to Paco₂ = 40 mm Hg, Po₂ = 40–50 mm Hg, and pH = 7.35. During hypocapnia, Paco₂ of artificial CSF was approximately 16 mm Hg and pH approximately 7.60.

Morphologic Studies

The carotid arteries, vertebral arteries, and circle of Willis were removed, examined for gross lesions, and fixed in buffered formalin. Histologic study of the carotid arteries was carried out on paraffin sections of preselected sites. Sections were stained with hematoxylin and eosin and Verhoeff-Van Gieson stain. Morphometric determination of the size of the intima and media was performed with an image analyzer as described previously.12,14

Statistical Analysis

Values for interventions were compared with the preceding control period with a one-way analysis of variance. Mean intergroup differences between normal, atherosclerotic, and regression monkeys were tested for significance with the Student-Newman-Keuls procedure.
Table 1. Intimal Area in Normal, Atherosclerotic, and Regression Monkeys

<table>
<thead>
<tr>
<th>Carotid artery</th>
<th>Normal</th>
<th>Atherosclerotic</th>
<th>Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal</td>
<td>0.06±0.06</td>
<td>1.92±0.48*</td>
<td>0.88±0.22</td>
</tr>
<tr>
<td>Middle</td>
<td>0</td>
<td>1.88±0.69*</td>
<td>0.43±0.12</td>
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<tr>
<td>Distal</td>
<td>0</td>
<td>1.76±0.50*</td>
<td>0.58±0.10</td>
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<tr>
<td>Vertebral artery</td>
<td>0</td>
<td>0.87±0.20*</td>
<td>0.28±0.10</td>
</tr>
</tbody>
</table>

Values are µm², mean±SEM. *p<0.05 vs. normal and regression monkeys.

Results

Plasma cholesterol was 96 ± 5 mg/dl in normal monkeys and 531 ± 39 mg/dl during the last 3 months of atherogenic diet in atherosclerotic monkeys. Plasma cholesterol in regression monkeys was 539 ± 47 mg/dl while they received atherogenic diet and 118 ± 10 when they received normal diet. Plasma triglycerides were <40 mg/dl in normal, atherosclerotic, and regression monkeys.

Morphologic Changes

In atherosclerotic monkeys, morphologic changes were similar to those described previously. The common and internal carotid arteries had pronounced atherosclerotic changes, with diffuse thickening of the vessel wall by virtually continuous lesions. The common carotid arteries demonstrated fibrofatty lesions with necrosis and calcification. Fatty streaks were the dominant lesion type in the extracranial internal carotid arteries. Intracranial arteries usually were virtually normal; lesions, when present, were limited to small fatty streaks. In regression monkeys, lipids were virtually absent in the extracranial arteries, but substantial fibrosis was present.

Morphometric study demonstrated significant increases in intimal area of the common carotid and vertebral arteries of atherosclerotic monkeys, with no significant increase in the intimal area of regression monkeys (Table 1). In both the carotid and vertebral arteries, medial area was similar in normal, atherosclerotic, and regression monkeys.

Cerebral Hemodynamics During Control Conditions

Before the interventions, pressure in pial arteries approximately 300 µm in diameter was 18–25 mm Hg lower than aortic pressure in normal, atherosclerotic, and regression monkeys (Table 2). Thus, large arteries (>300 µm in diameter) account for 25–30% of the vascular resistance in the cerebral circulation. This finding provides further support for the concept that large arteries as well as arterioles contribute importantly to cerebral vascular resistance in primates and other species.

Values for CBF obtained during the first control period appeared to be lower in regression monkeys than in normal or atherosclerotic monkeys (Table 2). This finding probably is of little importance because CBF during the second control period was similar in the 3 groups (Table 2).

Responses to Serotonin

The difference between aortic and pial arterial pressure increased during infusion of serotonin (Table 2, Figure 1). Serotonin reduced pial artery pressure (Fig-

Table 2. Cerebral Hemodynamics in Normal, Atherosclerotic, and Regression Monkeys

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Serotonin (µg/kg/min)</th>
<th></th>
<th>Control</th>
<th>Hypocapnia</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>8</td>
<td>40</td>
<td></td>
<td></td>
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<tr>
<td>Normal monkeys</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean aortic pressure (mm Hg)</td>
<td>71±2</td>
<td>74±6</td>
<td>71±3</td>
<td>75±5</td>
<td>70±4</td>
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<tr>
<td>Pial artery pressure (mm Hg)</td>
<td>53±2</td>
<td>52±5</td>
<td>45±3*</td>
<td>53±5</td>
<td>46±5</td>
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<tr>
<td>Change in pressure (mm Hg)</td>
<td>18±2</td>
<td>22±2</td>
<td>26±2*</td>
<td>22±2</td>
<td>24±3</td>
</tr>
<tr>
<td>Cerebral blood flow (ml/min/100 g)</td>
<td>31±2</td>
<td>28±2</td>
<td>34±3</td>
<td>30±2</td>
<td>24±4*</td>
</tr>
<tr>
<td>Atherosclerotic monkeys</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean aortic pressure (mm Hg)</td>
<td>80±7</td>
<td>82±8</td>
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<td>77±7</td>
<td>83±8</td>
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<tr>
<td>Pial artery pressure (mm Hg)</td>
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<td>36±5*</td>
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<td>61±5</td>
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<td>Change in pressure (mm Hg)</td>
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<td>33±7</td>
<td>42±9*</td>
<td>23±2</td>
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<td>Cerebral blood flow (ml/min/100 g)</td>
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<td>26±2</td>
<td>25±3</td>
<td>30±3</td>
<td>24±4*</td>
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<tr>
<td>Regression monkeys</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Mean aortic pressure (mm Hg)</td>
<td>89±5</td>
<td>87±6</td>
<td>83±5</td>
<td>85±5</td>
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<tr>
<td>Pial artery pressure (mm Hg)</td>
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<td>59±6</td>
<td>49±5*</td>
<td>57±4</td>
<td>60±5</td>
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<tr>
<td>Change in pressure (mm Hg)</td>
<td>25±3</td>
<td>29±3</td>
<td>34±3*</td>
<td>28±4</td>
<td>25±4</td>
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<tr>
<td>Cerebral blood flow (ml/min/100 g)</td>
<td>22±2</td>
<td>22±2</td>
<td>24±2</td>
<td>28±4</td>
<td>21±3*</td>
</tr>
</tbody>
</table>

Values are mean±SEM under control conditions, during infusion of serotonin into left atrium, and during hypocapnia produced by hyperventilation. Change in pressure from aorta to pial artery.

*p<0.05 vs. preceding control.
Normal Atherosclerotic Regression

A Pressure (mmHg)

Aorta to Pial Artery

μg Serotonin/kg per min

8  40  8  40  8  40  8  40

FIGURE 1. Cerebral vascular responses to infusion of serotonin into left atrium in normal, atherosclerotic, and regression monkeys. Values (mean ± SEM) indicate effects of serotonin on drop in pressure from aorta to pial arteries approximately 300 μm in diameter. *p<0.05 vs. normal and regression monkeys.

Normal Atherosclerotic Regression

A Large Artery Resistance

μg Serotonin/kg per min

8  40  8  40  8  40  8  40

FIGURE 3. Change in resistance (in mm Hg/ml·min·g) of large cerebral arteries in response to infusion of serotonin. Values are mean ± SEM; *p<0.05 vs. normal and regression monkeys.

atherosclerosis abolished the hyperresponsiveness to serotonin.

Responses to Hypocapnia

To test the specificity of altered cerebral vascular responses, effects of hypocapnia were examined. Hyperventilation significantly reduced CBF in normal, atherosclerotic, and regression monkeys (Table 2, Figure 4); the reduction was similar in the 3 groups. Hypocapnia did not alter the decrease in pressure from the aorta to pial artery in normal, atherosclerotic, and regression monkeys (Figure 4).

Thus, cerebral vasoconstrictor responses to hypocapnia were not altered by atherosclerosis or dietary treatment of atherosclerosis.

Discussion

We have suggested that the release of serotonin during aggregation of platelets at carotid lesions may produce vasoconstriction and contribute to the pathogenesis of transient cerebral ischemia. The major new finding in this study is that cerebral vasoconstrictor responses to serotonin, which were potentiated more than fivefold by atherosclerosis, were restored to normal by dietary treatment of atherosclerosis.
Methods

Insertion of a micropipette into pial arteries had no detectable effect on most vessels. Diameter of the vessel occasionally changed after insertion of the pipette, but changes were always transient. Hemorrhage at the puncture site occurred only when the pipette tip was removed from the vessel. No monkeys were excluded from the study because of spasm or hemorrhage produced by the pipette.

We measured blood flow to the entire ipsilateral cerebral hemisphere and measured pressure in a single pial artery. This approach (using a global measurement of blood flow and a local measurement of pressure) assumes that the craniotomy and micropipette do not alter blood flow to the region examined. In previous studies, we examined this assumption by separately measuring blood flow to brain tissue perfused by the pial artery in which we had measured pressure and in the remainder of the brain. Blood flow in these regions and the remainder of the cerebrum were similar under control conditions and during interventions. Thus, blood flow to the region under the pial window and to the area supplied by the punctured pial artery is similar to that to the entire hemisphere.

Serotonin constricts large extracranial arteries and thus decreases cerebral microvascular pressure. Despite constriction of large arteries, however, serotonin does not reduce CBF because small cerebral vessels dilate. The response of small vessels presumably is an autoregulatory response to the decrease in pial artery pressure. Thus, our experimental approach allowed detection of augmented vasoconstrictor responses to serotonin in atherosclerotic monkeys and restoration to normal during dietary treatment that would not have been detected if CBF, but not cerebral microvascular pressure, were measured.

The precise site of constriction of large arteries during infusion of serotonin is not known. Serotonin may constrict large extracranial arteries, or it may constrict large intracranial arteries proximal to the pial arteries in which pressure was measured. It seems likely that atherosclerotic alteration of responses to serotonin in this study occurred primarily in extracranial arteries because atherosclerotic lesions were confined to these vessels. Lipoproteins and hypercholesterolemia have been reported to alter the responses of pial arteries, however, even in the absence of atherosclerotic lesions. Thus, we cannot exclude the possibility that responses to serotonin are altered in large intracranial arteries, as well as in extracranial arteries, of atherosclerotic monkeys.

CBF was relatively low in this study, as in our previous studies of primates. The low values for CBF are not produced by arteriovenous shunting of microspheres in cats or dogs or in primates (F.M. Faraci and D.D. Heistad, unpublished observations). It is likely that the values for CBF were low because the monkeys were anesthetized and because the length of the experiment was usually 6-8 hours. These levels of blood flow probably do not compromise the validity of the findings, however, because vasoconstrictor responses, which were the focus of the study, were preserved.

Vascular Effects of Atherosclerosis and Regression

Primates develop atherosclerotic lesions in the carotid arteries that resemble those that occur in humans. There are marked increases in intimal area, with encroachment of the lesions into the lumen and impairment of maximal vasodilator responses. Regression of plaques in the carotid arteries has been demonstrated in humans. During dietary treatment of atherosclerosis in primates, intimal area is reduced as the lesions regress. There is a tendency for intimal fibrosis to progress, however, during dietary treatment of atherosclerosis so that in some vascular beds maximal vasodilator responses fail to improve. In cerebral vessels, regression of atherosclerosis is accompanied by marked improvement in vasodilator responses.

Vasospasm clearly is an important complication of coronary atherosclerosis, but it is not clear whether atherosclerosis predisposes to vasospasm in other vascular beds, including the cerebral circulation. Changes in endothelial function may contribute to alteration of vascular responses and susceptibility to vasospasm in atherosclerotic arteries. Endothelium-dependent relaxing factor modulates responses to many vasoactive substances including exogenous serotonin and serotonin that is released by platelets. Recent studies indicate that atherosclerosis impairs endothelium-dependent vascular responses. Synthesis of endothelium-dependent relaxing factor is impaired in atherosclerotic vessels.

A preliminary report suggests that treatment of atherosclerosis restores endothelium-dependent vascular responses to normal. We speculate, therefore, that one mechanism by which hyperresponsiveness to serotonin in the cerebral circulation is abolished during dietary treatment of atherosclerosis may involve restoration of normal endothelium-dependent responses. Vasoconstrictor responses to hypoxemia, in contrast to responses to serotonin, were not altered by atherosclerosis or dietary treatment. Thus, alteration of responses may be somewhat specific for serotonin.

We have estimated the concentration of serotonin that was achieved during its infusion in these experiments and compared this value with blood levels that have been observed in vivo. We assumed that 90% of the serotonin is cleared in 1 passage through the pulmonary circulation, that circulation time in monkeys is 14 seconds, and that the space of distribution is limited to plasma. We thereby estimated that infusion of 8 and 40 μg/kg/min serotonin into the left atrium produces plasma concentrations of 43 and 215 ng/ml. For comparison, partial occlusion of a coronary artery with a thrombus increases the level of serotonin in blood distal to the occlusion from 9 to 213 ng/ml. Thus, the blood levels of serotonin that were achieved in this study probably are similar to those that may occur in pathophysiologic states. Furthermore, the concentration of serotonin in arterial segments under a
thrombus has been reported to increase to > 800 ng/g of vessel.13

Implications

Most TIAs apparently are produced by the aggregation of platelets in extracranial arteries.7 Release of serotonin during platelet aggregation may contribute to the pathogenesis of TIAs.6 Serotonin constricts large extracranial arteries and reduces distal pressure so that, in the presence of fixed stenosis of a small artery or partial obstruction by an embolus, it may contribute to focal cerebral ischemia. We now suggest that dietary treatment of atherosclerosis, by abolishing the hyperresponsiveness to serotonin in the cerebral circulation, may reduce susceptibility to TIAs.

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Key Words • atherosclerosis • serotonin • microvascular pressure • cynomolgus monkeys
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