Dietary Treatment of Atherosclerosis Abolishes Hyperresponsiveness to Serotonin: Implications for Vasospasm

Donald D. Heistad, Allyn L. Mark, Melvin L. Marcus, Donald J. Piegors, and Mark L. Armstrong

Diet-induced atherosclerosis in primates impairs vasodilator responses and greatly potentiates vasoconstrictor responses to serotonin. Serotonin may play an important role in the pathogenesis of vasospasm. In diet-induced regression of atherosclerosis, intimal lesions are reduced, but maximal vasodilator responses do not improve, perhaps because of vascular fibrosis. Our goal was to determine whether dietary treatment of atherosclerosis reverses the augmented vasoconstrictor responses to serotonin and thus might reduce susceptibility to vasospasm. Normal cynomolgus monkeys, atherosclerotic monkeys, and atherosclerotic monkeys that were given a normal (regression) diet for 18 months were studied. Morphometric studies indicated that the regression diet reduced lesions in the iliac and femoral artery since intimal area was reduced by about 50%. In the hind limb perfused at constant flow, residual resistance during maximal vasodilatation produced by infusion of adenosine tended to be greater in atherosclerotic monkeys than in normals and failed to improve in regression monkeys. In contrast, vasoconstrictor responses to serotonin were greatly potentiated in atherosclerotic monkeys and were restored to normal in regression monkeys. Serotonin (20 μg i.a.) decreased hind limb resistance (in mm Hg/ml/min) 0.34 ± 0.06 (mean ± SE) in normal monkeys, increased resistance 0.58 ± 0.17 in atherosclerotic monkeys (p < 0.05 vs. normal), and decreased resistance 0.70 ± 0.15 in regression monkeys (p < 0.05 vs. atherosclerotic). Thus, dietary treatment of atherosclerosis abolishes augmented vasoconstrictor responses to serotonin. It is proposed that treatment of atherosclerosis may be beneficial, even when vasodilator responses fail to improve, by reducing susceptibility to serotonin-induced vasospasm. (Circulation Research 1987;61:346-351)

Dietary treatment of atherosclerosis in primates results in morphologic evidence for regression of lesions with reduction in lesion size and a marked reduction in intimal lipids. Vasodilator responses remain markedly impaired, however, after dietary treatment of atherosclerosis, especially in the limb. It is likely that vascular fibrosis, which occurs during regression of atherosclerosis, limits hemodynamic improvement.

An important concept which has emerged in the last few years is that atherosclerosis predisposes to vasospasm in addition to limiting maximal vasodilator responses. Serotonin, which is present in substantial concentrations in platelets and may be released when platelets aggregate at atherosclerotic lesions, produces marked constriction in atherosclerotic vessels. Thus, serotonin has been implicated as a possible mediator in the pathogenesis of vasospasm. Increased cholesterol content of membranes, an increase in the number of serotonergic receptors, and alteration of endothelium-dependent vascular responses are potential mechanisms by which atherosclerosis potentiates vasoconstrictor responses to serotonin.

The purpose of this study was to determine whether dietary treatment of atherosclerosis affects hyperresponsiveness to serotonin. It was hypothesized that because mechanisms by which atherosclerosis impairs vasodilatation and potentiates vasoconstrictor responses to serotonin probably differ, hemodynamic consequences of regression of atherosclerosis also may differ in relation to limitation of maximal vasodilator responses and hyperresponsiveness to serotonin. Thus, the present study examined the possibility that dietary treatment of atherosclerosis might reduce hyperresponsiveness to serotonin despite failure to improve maximal vasodilator responses.

Materials and Methods

Three groups of male Malaysian cynomolgus monkeys were studied: normal, atherosclerotic, and regression. Eight normal monkeys (weight 5.8 ± 0.2 kg, mean ± SEM) were fed commercial laboratory chow.
(Purina Monkey Chow,Ralston Purina Co., Richmond, Ind.). Eight atherosclerotic monkeys (weight 5.9 ± 0.3 kg) were fed atherogenic diet for 18–22 months. The atherogenic diet contained 41% of total calories as fat and 0.8% cholesterol. Eight regression monkeys (weight 5.9 ± 0.3 kg) were fed the same atherogenic diet for 18 months and then were placed on commercial laboratory chow for 18–20 months. At intervals of 3–4 months, venous blood samples were obtained after sedation with ketamine hydrochloride (10 mg/kg i.m.). Total cholesterol and triglycerides were determined by the method used by the Lipid Research Clinics Protocol for the Autoanalyzer II (Technicon Instruments Inc., Tarrytown, N.Y.).

Hemodynamic Studies

The monkeys were sedated with ketamine hydrochloride (10 mg/kg i.m.) and then anesthetized with α-chloralose (100 mg/kg i.v.). Supplemental doses of chloralose were given as needed. Catheters (PE-90) were placed in a brachial vein for administration of drugs and in a brachial artery for monitoring blood pressure and blood gases. A tracheotomy was performed, and the animals were intubated and ventilated with room air and supplemental oxygen using a respirator. Gallamine triethiodide (4 mg/kg i.v.) was administered for skeletal muscle paralysis and heparin sodium (500 U/kg i.v.) for anticoagulation.

Through a laparotomy, the bifurcation of the abdominal aorta and the proximal left iliac artery was exposed. The left dorsal pedal artery was exposed, and a PE-50 catheter was inserted retrogradely to measure pressure. The left hypogastric artery was cannulated retrogradely with a PE-90 catheter to record pressure in the iliac artery. For perfusion of the hind limb, the abdominal aorta was cannulated retrogradely, and blood was pumped through a cannula placed antegrade in the proximal left iliac artery. The limb was perfused with pulsatile pressure (about 30 mm Hg pulse pressure). Blood flow to the limb was adjusted prior to interventions so that iliac perfusion pressure was similar to systemic arterial pressure. In some atherosclerotic and regression monkeys, initial blood flow to the limb was considerably lower than in normal monkeys. Blood flow to the limb was then increased, which tended to raise iliac perfusion pressure above the level observed in normal monkeys.

Maximal perfusion pressure and pressure in the dorsal pedal artery were measured during bolus injections of 5 and 20 μg of serotonin (5-hydroxytryptamine as creatine sulfate complex) and 5 and 20 μg of phenylephrine hydrochloride. Maximal vasodilator responses were studied by infusion of adenosine at 1.34 mg/min into the perfusion tubing. Infusion of higher doses of adenosine produced no greater vasodilatation.

Hind limb vascular resistance was calculated by dividing iliac perfusion pressure by blood flow through the perfused iliac artery. The difference between iliac pressure and dorsal pedal pressure indicates large artery resistance in the limb. The method has been described in detail previously. 14

Morphologic Studies

The monkeys were killed with KCl i.v. The iliac and femoral arteries were removed and fixed by immersion in formalin. Specimens were taken at standardized sites from the proximal and midsegment of the iliac artery and proximal and midsegment of the femoral artery as defined previously. 7 Specimens were prepared for microscopy, and paraffin sections were taken for histologic study.

Morphometric comparisons were made using methods and calculations described previously. 7 The specimens were projected, and cross-sectional areas of the intima and media were digitized.

Statistical Analysis

Mean values and variance were analyzed with a split-plot design, using repeated measures analysis with the Bonferroni multiple comparison test. Statistical significance was considered as p < 0.05.

Results

Plasma Lipids

Plasma total cholesterol was 132 ± 23 mg/dl in normal monkeys and 554 ± 19 mg/dl in atherosclerotic monkeys. Plasma cholesterol in regression monkeys was 565 ± 33 while they received atherogenic diet and 113 ± 8 when they received regression (normal) diet. Plasma triglycerides were < 40 mg/dl in all 3 groups.

Morphologic Changes

In atherosclerotic monkeys, morphologic changes were similar to those described previously. 2,4,8 There was dense fibrofatty intimal thickening with focal intimal necrosis in the aorta and its major branches, including the iliac arteries and the proximal part of the femoral arteries. Intimal thickening in the midportion of the femoral arteries consisted largely of fatty streak lesions.

Morphometry demonstrated increases in intimal area in the iliac and femoral arteries of atherosclerotic monkeys (Table 1). Intimal area was less in regression

<table>
<thead>
<tr>
<th>Table 1. Arterial Morphometric Values</th>
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<tbody>
<tr>
<td>Normal</td>
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<td>------------------</td>
</tr>
<tr>
<td>Proximal iliac</td>
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<tr>
<td>Intima</td>
</tr>
<tr>
<td>Media</td>
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<tr>
<td>Midiliac</td>
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<td>Proximal femoral</td>
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<tr>
<td>Midfemoral</td>
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<td>Intima</td>
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<tr>
<td>Media</td>
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* p < 0.05 vs. normal. †p < 0.05 vs. atherosclerotic.
monkeys than in atherosclerotic monkeys in midiliac and midfemoral arteries. Medial area was not significantly different in normal and regression monkeys although medial area tended to be increased in atherosclerotic arteries.

**Hemodynamic Studies**

**Baseline Values.** Total hind limb vascular resistance and large artery resistance were not significantly different in normal and atherosclerotic monkeys (Table 2) although the values tended to be increased in atherosclerotic monkeys. Hind limb resistance was similar in atherosclerotic and regression monkeys.

During infusion of adenosine, vascular resistance in the total limb and in the large artery segment tended to be higher in atherosclerotic than normal monkeys, but differences did not achieve statistical significance (Figure 1). These values were similar in atherosclerotic and regression monkeys (Figure 1). Thus, atherosclerosis and regression did not produce consistent changes in baseline resistance or responses to adenosine.

**Responses to Serotonin.** Serotonin produced vasodilatation in the limb (reduction in iliac perfusion pressure) in normal monkeys (Figure 2). In contrast, serotonin produced vasoconstrictor responses in atherosclerotic monkeys (*p < 0.05 vs. normal monkeys*). Vascular responses to serotonin were restored to dilatation in regression monkeys (*p < 0.05 vs. atherosclerotic monkeys*) as shown in Figure 2. Vasodilator responses to serotonin tended to be greater (but *p > 0.05*) in regression monkeys than in normal monkeys, perhaps because baseline resistance in the hind limb tended to be higher in regression monkeys than in normal monkeys (Table 2).

Serotonin produced minimal constriction of the large artery segment in the limb of normal monkeys (Figure 3). This response to serotonin was greatly potentiated in atherosclerotic monkeys (*p < 0.05 vs. normal monkeys*). The response to serotonin was restored to normal levels in regression monkeys (*p < 0.05 vs. atherosclerotic monkeys*).

**Responses to Phenylephrine.** To test the specificity of altered vascular responses, effects of phenylephrine were examined. Vasoconstrictor responses to phenylephrine in the hind limb were similar in normal and atherosclerotic monkeys (Figure 4). Responses to 20 μg (but not 5 μg) phenylephrine were significantly augmented in regression monkeys (*p < 0.05 vs. normal and atherosclerotic monkeys*). It is possible that the augmented response to phenylephrine in regression monkeys is related in some way to elevation of baseline iliac perfusion pressure (Table 2). Phenylephrine produced modest constriction of the large artery segment in the limb of normal monkeys (Figure 5). This response was not significantly different in atherosclerotic or regression monkeys (*p > 0.05*).

**Table 2. Baseline Hemodynamic Values**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Normal</th>
<th>Atherosclerotic</th>
<th>Regression</th>
</tr>
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<tbody>
<tr>
<td>Mean arterial pressure (mm Hg)</td>
<td>80 ± 4</td>
<td>74 ± 5</td>
<td>79 ± 6</td>
</tr>
<tr>
<td>Hind limb blood flow (ml/min)</td>
<td>65 ± 8</td>
<td>56 ± 6</td>
<td>57 ± 6</td>
</tr>
<tr>
<td>Iliac perfusion pressure (mm Hg)</td>
<td>87 ± 6</td>
<td>99 ± 4</td>
<td>106 ± 4*</td>
</tr>
<tr>
<td>Hind limb vascular resistance</td>
<td>1.44 ± 0.15</td>
<td>1.99 ± 0.24</td>
<td>1.96 ± 0.18</td>
</tr>
<tr>
<td>(mm Hg/ml/min)</td>
<td></td>
<td></td>
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<tr>
<td>Large artery pressure gradient</td>
<td>26 ± 4</td>
<td>36 ± 7</td>
<td>25 ± 3</td>
</tr>
<tr>
<td>(iliac-dorsal pedal pressure, mm Hg)</td>
<td></td>
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<tr>
<td>Large artery resistance (mm Hg/ml/min)</td>
<td>0.41 ± 0.07</td>
<td>0.75 ± 0.21</td>
<td>0.45 ± 0.05</td>
</tr>
</tbody>
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Values are mean ± SEM in 8 normal, 8 atherosclerotic, and 8 regression monkeys. *p < 0.05 vs. normal; other variables were not significantly different in normal, atherosclerotic, and regression monkeys.

**Figure 1.** Vascular resistance during infusion of adenosine in perfused hind limb of normal, atherosclerotic (AS), and regression monkeys. Values (mean ± SEM) are resistance in total hind limb (left) and in large artery segment from iliac artery to dorsal pedal artery (right). Values are not significantly different (*p > 0.05*).

**Figure 2.** Responses to intra-arterial injections of serotonin in perfused hind limb. Values (mean ± SEM) are changes in total hind limb (or iliac) perfusion pressure. Increases in perfusion pressure indicate vasoconstriction, and decreases indicate vasodilatation. Responses to serotonin were different in atherosclerotic monkeys compared with normal and regression groups (* = *p < 0.05*).


Discussion

The striking new finding in this study is that vasocostrictor responses to serotonin, which were greatly potentiated by atherosclerosis, were restored to normal by dietary treatment of atherosclerosis. The observation that regression of atherosclerosis did not alter maximal vasodilator responses but completely corrected the hyperresponsiveness to serotonin implies that different mechanisms account for these hemodynamic abnormalities.

Vascular Effects of Atherosclerosis and Regression

Experimental atherosclerosis in primates, as well as human atherosclerosis, is associated with marked proliferation of intima.1-3 A surprising new concept, which was proposed by Bond et al22 and which is supported by several studies in primates5-24 and man,25 is that marked intimal proliferation often is associated with little or no encroachment on the vascular lumen. Thus, the vascular lumen may be preserved completely despite severe atherosclerotic lesions,1-22-25 probably because of vessel growth or remodeling.

Maximal vasodilator responses are impaired in the limb and other vascular beds in atherosclerotic primates.5,24 Impairment of the maximal vasodilator response was demonstrated in the limb by a shift in the pressure-flow relation.5,24 In this study, in which one value for pressure and flow was obtained, minimum resistance tended to be increased by atherosclerosis although the difference did not achieve statistical significance. It is likely that determination of the pressure-flow relation, which is more sensitive than measurement of one value of pressure and flow, would have demonstrated a significant increase in resistance in atherosclerotic monkeys. The modest change in minimal resistance in the atherosclerotic limb,5,24 despite marked intimal proliferation, must be related to the relative preservation of the vascular lumen.1,22-24

Several studies in the limb and other vascular beds have demonstrated that intimal area is reduced during regression of atherosclerosis.1-9 These studies provide strong evidence that dietary treatment of atherosclerosis leads to morphologic improvement in atherosclerotic vessels. There is a tendency for intimal fibrosis to become more marked, however, during regression of atherosclerosis in cynomolgus monkeys.5-10 A previous study reported the disappointing finding that dietary treatment of atherosclerosis produced no change of maximal vasodilator responses in the limb or coronary circulation,2 presumably because intimal fibrosis prevented hemodynamic improvement. In this study also, no improvement of maximal vasodilator responses to adenosine was found during regression of atherosclerosis.

Pathogenesis of Vasospasm

Vasospasm is an important complication of atherosclerotic cardiovascular disease.11 Vasospasm occurs spontaneously11 and in susceptible patients may be induced by ergonovine.26 Potentiation of vasoconstrictor responses to ergonovine appears to be mediated largely by serotoninergic receptors.15

It is not yet clear which vasoactive substances are of primary importance in the pathogenesis of vasospasm. Serotonin, thromboxane, thrombin, adrenergic stimuli, and histamine are some potential mediators of vasospasm.15
Mechanisms of Altered Vascular Responses during Atherosclerosis

Serotonin is an important mediator of vasospasm. Platelets contain large quantities of serotonin. In experimental animals, serotonin constricted large arteries but dilated small arteries. In normal monkeys, serotonin may play an important role in alteration of vascular responses to serotonin at the level of large arteries, and they appeared to increase responses to serotonin in the large artery segment. Vasoconstrictor responses to serotonin are increased in large arteries of atherosclerotic vessels and release serotonin. Serotonin also is released by the endothelium in response to injury, and release of serotonin is increased in large arteries with atherosclerosis. Several recent studies indicate that atherosclerosis impairs endothelium-dependent vascular responses. A preliminary report suggests that regression of atherosclerosis restores endothelium-dependent vascular responses. A preliminary report suggests that regression of atherosclerosis restores endothelium-dependent vascular responses.

The findings in this study may have important implications for dietary treatment of atherosclerosis. In part by restoration of normal responsiveness to serotonin, dietary treatment may correct the abnormality. One might anticipate that a dietary treatment that can correct the abnormality may play an important role in treatment of vascular disease. The findings in this study may have important implications for dietary treatment of atherosclerosis. In part by restoration of normal responsiveness to serotonin, dietary treatment may correct the abnormality. One might anticipate that a dietary treatment that can correct the abnormality may play an important role in treatment of vascular disease.

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References


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