The paradox of adrenergic coronary vasoconstriction

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RECENT OBSERVATIONS demonstrate adrenergic coronary vasoconstriction during exercise and other circumstances that result in generalized sympathetic activation. Coronary vasoconstriction seems paradoxical during tachycardia when coronary flow must increase to supply an augmented myocardial oxygen demand. However, there is evidence that adrenergic coronary vasoconstriction is beneficial in maintaining an even distribution of transmural blood flow.

This essay will develop the theme that adrenergic coronary vasoconstriction is a normal part of generalized sympathetic activation and serves to help maintain a uniform transmural distribution of blood flow in the wall of the left ventricle. The experimental results from animal studies will be reviewed first, and the conclusions will then be used to interpret the findings from clinical studies of patients with angina.

The physiologic basis of the concepts presented here has been extensively reviewed, and only a subset of the literature will be cited.1

Experimental animal studies

α-Receptor–mediated vasoconstriction. Electrical stimulation of sympathetic fibers that innervate the heart and coronary vessels results in tachycardia, increased myocardial contractility, and thus augmented myocardial oxygen consumption. The increased myocardial metabolism causes a secondary coronary vasodilation by a local mechanism. Paradoxically, there is a concomitant adrenergic coronary vasoconstrictor effect that limits the metabolic vasodilation and results in an augmented myocardial arteriovenous oxygen difference. Although the net effect of sympathetic activation is almost always an increase in coronary blood flow, the coronary vasoconstrictor effect retards the metabolic vasodilation by about 20% to 30%; hence, there is a coexisting coronary vasoconstriction while total coronary flow is increasing.2

The cardiac chronotropic and inotropic effects of sympathetic activation are mediated via β-receptors and can be blunted by β-receptor–blocking agents. Thus it is possible to “unmask” sympathetic coronary vasoconstriction by prior β-receptor blockade (since the vasoconstriction is mediated by α-receptors).3 After β-receptor blockade the usual response to sympathetic activation is a net decrease in coronary blood flow; hence, vasoconstriction is “unmasked.”

Intracoronary infusions of norepinephrine before and after β-receptor blockade give results consistent with this interpretation of metabolic vasodilation secondary to myocardial β-receptor activation and direct α-receptor–mediated vasoconstriction.4 Intracoronary infusion of selective α-receptor agonists such as phenylephrine also results in coronary vasoconstriction.5

Thus, in the absence of β-blockade, the interpretation is that α-receptor–mediated coronary vasoconstriction competes with local metabolic vasodilation secondary to cardiac chronotropic and inotropic effects when sympathetic nerves are activated or norepinephrine is infused into the coronary artery.2

α-Receptor subtype. α-Adrenoceptors may be subdivided into types 1 and 2 on the basis of selective agonists and antagonists.6–8

It was originally suggested that α₁-receptors are located on the postjunctional effector cell and α₂-receptors are located on the presynaptic sympathetic neuron. However, this anatomic designation is inconsistent with pharmacologic results that demonstrate both α₁- and α₂-receptors on postjunctional cells. Canine coronary vascular smooth muscle has α₁- and α₂-receptors and both subserve vasoconstriction.
The $\alpha_1$- and $\alpha_2$-mediated vasoconstriction secondary to electrical stimulation of cardiac sympathetic fibers in a previously $\beta$-blocked preparation has been demonstrated with the $\alpha_1$-selective antagonist prazosin and the $\alpha_2$-selective antagonists rauwolscine and idazoxan.9–12 Similar results are obtained with intracoronary infusions of norepinephrine.9, 13 Consistent results are also obtained with selective $\alpha_1$- (clonidine, methoxamine) and $\alpha_2$- (BHT 920, $\alpha$-methylnorepinephrine) agonists, although the selectivity of some of these agonists is not very great.9, 14

**Large vs small vessel effects.** Under normal resting conditions, the large (epicardial) coronary arteries contribute less than 5% to the total coronary resistance. However, this percentage increases during high-flow states (e.g., exercise), especially if there is atherosclerotic narrowing of the artery.15 Electrical stimulation of cardiac sympathetic nerves or intracoronary infusion of norepinephrine in a previously $\beta$-blocked preparation results in an epicardial vasoconstriction that is about 65% of the increase in small vessel resistance.16–20 Therefore the conclusion is that although epicardial arteries participate in adrenergic vasoconstriction, the dominant site of the resulting resistance change is in arterioles distal to the epicardial vessels, because the conduit vessels constitute a small fraction of the total resistance.

Current evidence indicates that adrenergic vasoconstriction of large coronary vessels is predominantly mediated via $\alpha_1$-receptors in contrast to resistance vessels, where both $\alpha_1$- and $\alpha_2$-receptors are involved.9, 20–22

**Collateral vessels.** Slow or repeated intermittent closure of a major coronary artery stimulates collateral hypertrophy in experimental animals. There is conflicting evidence concerning the sensitivity of collateral vessels to $\alpha$-receptor agonists. Some investigators find no evidence for collateral vasoconstriction mediated by $\alpha$-receptors,23, 24 while others do.25–27 The reasons for the divergent results are not apparent at this time.

**$\beta$-Receptor vasodilation.** In addition to $\alpha$-receptors, coronary vascular smooth muscle also has $\beta$-receptors that subserve vasodilation. Experiments in vivo indicate that small coronary resistance vessels have $\beta_2$-receptors that can be pharmacologically activated by isoproterenol, and slightly by epinephrine, but that are essentially unaffected by norepinephrine or sympathetic nerve activation.1, 28, 29 The $\beta$-receptor subtype of large coronary vessels is indistinct, since there is evidence in vivo and in vitro for both $\beta_1$- and $\beta_2$-receptors in epicardial arteries.20, 30–33

**Resting sympathetic vasoconstrictor tone.** Holtz et al.34 produced regional cardiac sympathectomy with local infusions of 6-hydroxydopamine and then compared coronary blood flow in normal and sympathectomized regions of the same heart. In unanesthetized dogs the resting blood flow was about 60% greater in the chemically sympathectomized region than in the normal region, indicating a surprisingly large resting sympathetic vasoconstrictor tone. Chilian et al.35 used selective epicardial incisions and phenol application to produce regional cardiac sympathectomy and then compared blood flow in the normal and sympathectomized regions under unanesthetized, resting conditions. When the animals were in a true basal resting state with low circulating levels of catecholamines, no difference in coronary blood flow was found between the innervated and denervated regions. This indicates that, as in the renal circulation, there is little resting sympathetic tone in the coronary circulation.

It is difficult to reconcile the Holz and Chilian studies, and the level of resting sympathetic vasoconstrictor tone in the coronary circulation is not clearly established. In other studies the incidental finding that $\alpha$-receptor blockade does not change resting coronary sinus oxygen tension is consistent with an insignificant level of resting tone, and this is the usual conclusion at the present time.

**Carotid baroreceptor reflex.** Lowering carotid sinus pressure produces reflex tachycardia and peripheral vasoconstriction that increases aortic blood pressure. The tachycardia results from parasympathetic inhibition and sympathetic activation, whereas the peripheral vasoconstriction is mediated via the sympathetic nervous system. Although there is a net increase in coronary blood flow during a baroreceptor reflex elicited by carotid sinus hypotension, there is a concomitant $\alpha$-receptor-mediated vasoconstriction that competes with the metabolic vasodilation secondary to the tachycardia and augmented left ventricular afterload.2 The coronary vasoconstrictor component of the baroreceptor reflex has been observed in several laboratories, and the $\beta$-receptor–mediated cardiac effects and $\alpha$-receptor–mediated coronary vasoconstriction have been demonstrated with selective blocking agents.1, 36–38 The coronary vasoconstrictor component of the reflex is paradoxical, since coronary blood flow must increase to provide the oxygen required by the tachycardia and augmented left ventricular afterload. As will be developed below, the adrenergic coronary vasoconstriction may serve to help preserve blood flow to the inner layers of the left ventricle.

**Exercise.** There is a generalized sympathetic activation during exercise that results in tachycardia, an
increase in blood pressure, and elevated levels of plasma catecholamines. During strenuous exercise, heart rate and myocardial oxygen metabolism are four to five times greater than at rest. Comparison of the coronary flow response to exercise before and after combined $\alpha_1$- and $\alpha_2$-blockade with phentolamine indicates that flow is restricted as much as 30% by adrenergic vasoconstriction.\textsuperscript{39-43} Thus despite the intense local metabolic vasodilation, there is a concomitant $\alpha$-receptor–mediated vasoconstrictor effect that limits the increase in coronary blood flow.

The use of a combined $\alpha_1$, $\alpha_2$-antagonist during exercise is consistent with the demonstration that coronary smooth muscle has both $\alpha_1$- and $\alpha_2$-vasoconstrictor receptors, although part of the response to phentolamine is probably due to blockade of prejunctional $\alpha_2$-receptors. Such a blockade increases sympathetic norepinephrine release and augments flow via a local metabolic mechanism secondary to stimulation of myocardial $\beta$-receptors.\textsuperscript{44, 45} However, adrenergic coronary vasoconstriction independent of prejunctional $\alpha_2$-receptors has been demonstrated by intracoronary injection of the $\alpha_1$-selective antagonist prazosin or phentolamine in a previously $\beta$-blocked preparation during exercise.\textsuperscript{46}

**Emotion.** Adrenergic coronary vasoconstriction has been demonstrated during sympathetic activation in a conditioned emotional response when an auditory tone precedes an unavoidable noxious stimulus.\textsuperscript{47} A significant decrease in coronary flow has been described in the post-anger state, but an adrenergic mechanism has not been tested yet.\textsuperscript{48}

**Hypoperfusion.** The studies cited above indicate that adrenergic coronary vasoconstriction is robust enough to compete with local metabolic vasodilation during functional hyperemia in a number of circumstances. Another question is whether adrenergic vasoconstriction acts during ischemic vasodilation. The answer is a qualified yes. One group of papers indicates that adrenergic vasoconstriction can compete with modest ischemic vasodilation, but is not powerful enough to worsen the ischemia to the extent that the heart produces lactate.\textsuperscript{11, 12, 49-52} A second group of studies indicates that $\alpha$-adrenergic vasoconstriction can worsen ischemia to the extent of causing ST segment changes in the electrocardiogram\textsuperscript{53} and lactate production.\textsuperscript{54} Heusch and Deussen\textsuperscript{54, 55} even presented evidence that myocardial ischemia potentiates adrenergic coronary vasoconstriction and emphasized that the vasoconstriction in this case is mediated by $\alpha_2$, rather than $\alpha_1$, receptors.

**Transmural adrenergic vasoconstriction.** The transmural distribution of adrenergic coronary vasoconstriction has been studied with microspheres in several laboratories. The usual experiment has been to activate adrenergic coronary vasoconstriction by sympathetic nerve stimulation or intracoronary infusions of catecholamines in a previously $\beta$-blocked preparation. During normal conditions without flow limitation, sympathetic stimulation results in a uniform transmural distribution of adrenergic vasoconstriction\textsuperscript{56} or a somewhat greater vasoconstriction in the outer than the inner layer of the left ventricle.\textsuperscript{57, 58} Intracoronary infusion of norepinephrine results in a uniform transmural adrenergic vasoconstriction in the left ventricle.\textsuperscript{43, 50, 56, 59}

**Adrenergic anti-transmural steal.** With each systole the ventricular myocardium squeezes the coronary circulation, essentially stopping flow into the arteries. The systolic compressive forces are greatest in the innermost layers of the ventricle and less in the outer layers near the epicardium. This means that the inner layer of the myocardium is perfused primarily during diastole. The normal inner/outer layer ratio of blood flow in the left ventricle is approximately 1.1 but falls sharply if coronary flow is limited by a stenosis. During ischemia a portion of the decrease in the inner/outer flow ratio is caused by a transmural vascular steal whereby the proximal outer layer receives a greater fraction of the flow, thus limiting the inner layer flow even further. A vascular steal occurs when perfusion pressure for a vasodilated vascular bed (in which flow is pressure dependent) is lowered by vasodilation in a parallel vascular bed, both beds being distal to a stenosis. Since the outer layers of the left ventricle are subject to less compressive force than the inner layers, the outer layer vascular bed steals flow from the inner layer. A stenosis may not lower the distal pressure much during rest when flow is low, but the pressure loss across the stenosis may become severe during functional hyperemia. The problem is exacerbated by tachycardia because the duration of diastole is abbreviated, thus limiting the time available for inner layer flow.

Buffington and Feig\textsuperscript{50} examined the transmural distribution of $\alpha$-receptor–mediated coronary vasoconstriction during graded hypoperfusion using constant pressures in the cannulated coronary artery. No difference in the inner/outer ratio of adrenergic vasoconstriction was observed at servo-controlled coronary artery pressures of 100, 70, 50, and 38 mm Hg. A transmural vascular steal was not possible in this preparation, however, because coronary artery pressure was held constant at a given level (vasoconstriction or dilation in one layer could not change the perfusion pressure for the other layer).
Nathan and Feigl \cite{59} did a very similar experiment, except that a constant flow preparation was used. A constant flow preparation mimics a stenosis and permits a vascular steal, since vasoconstriction or dilation in one layer of the ventricle will change the perfusion pressure for the other layer. The effects of adrenergic vasoconstriction were studied when flow was held constant at 100%, 80%, 70%, 60%, and 50% of control flow. Under these conditions, $\alpha$-receptor--mediated vasoconstriction in the outer layer of the left ventricle improved flow to the inner layer. Thus there was an adrenergic effect during hypoperfusion that resulted in a more uniform transmural distribution of the available flow. The probable mechanism is that the ischemic vasoconstriction is less severe in the outer layer of the left ventricle than in the inner layer, allowing adrenergic vasoconstriction to compete more effectively in the outer layer. With fixed flow, vasoconstriction in the outer layer increases the perfusion pressure for pressure--dependent flow in the inner layer, producing an antistean effect. Chilian and Ackell \cite{60} have recently demonstrated the same effect in exercising dogs with a coronary artery stenosis and a portion of ventricle surgically sympathectomized. The inner/outer flow ratio distal to the stenosis was better maintained in the innervated region than in the sympathectomized region.

Transmural flow during exercise. Despite the intense coronary vasodilation and very brief diastoles that occur during the tachycardia of exercise, blood flow to the inner layer of the left ventricle is not compromised and the inner/outer flow ratio remains close to 1.0. \cite{61--63} The uniform transmural blood flow during exercise is in contrast to the inner/outer flow ratio of 0.4 that is observed when comparable vasodilatation and tachycardia are produced by adenosine and cardiac pacing. \cite{64} Clearly there are differences between exercise and pharmacologic coronary vasodilatation combined with tachycardia. As discussed above, one of the differences is that generalized sympathetic activation during exercise includes an $\alpha$-receptor--mediated coronary vasoconstrictor effect.

Huang and Feigl \cite{65} tested the hypothesis that $\alpha$-adrenergic coronary vasoconstriction helps maintain a uniform transmural distribution of myocardial blood flow during exercise. Radioactive microspheres were used to make paired comparisons of flow between $\alpha$-blocked and $\alpha$-intact regions of the left ventricle during graded treadmill exercise in dogs. The transmural distribution of blood flow was more uniform, and flow in the inner layer of the left ventricle was better maintained, with $\alpha$-receptors intact than with $\alpha$-receptors blocked. This indicates that adrenergic coronary vasoconstriction has a beneficial effect during exercise. This beneficial effect on transmural blood flow in the absence of a stenosis may resolve the paradox of adrenergic coronary vasoconstriction during tachycardia. The hypothesis is that the organism has adapted adrenergic vasoconstriction in the coronary circulation to help overcome systolic compression that impedes flow to the inner layer of the left ventricle during the metabolic vasodilation and tachycardia of exercise.

The mechanism by which adrenergic vasoconstriction improves transmural flow distribution has not been determined. In the absence of a coronary stenosis, an anti-transmural steal mechanism seems unlikely, although it is possible that conductance vessels contribute significant resistance with the high flows that occur during exercise. An additional possible mechanism may involve changes in vascular capacitance and vessel wall stiffness. \cite{66} Myocardial vessels are narrowed by systolic compression, therefore some diastolic time is spent reexpanding narrowed vessels and filling their capacitance before flow through the vessels resumes. Stiffening of the vessel wall by vasoconstriction may help the vessel resist narrowing during systole and may also facilitate reexpansion during diastole.

Conclusion — animal studies. The experimental work discussed above indicates that adrenergic coronary vasoconstriction occurs in both large and small coronary vessels, but the dominant effect is in small vessels. The small-vessel vasoconstriction is mediated by post-junctional $\alpha_1$- and $\alpha_2$-receptors. Although resting sympathetic vasoconstrictor tone is low, adrenergic coronary vasoconstriction is a normal part of generalized sympathetic activation during baroreceptor reflexes, exercise, and emotion. In the absence of coronary stenosis there is a fairly uniform transmural distribution of adrenergic vasoconstriction, but in the presence of flow limitation an anti-transmural steal effect is observed. During exercise adrenergic coronary vasoconstriction helps maintain a uniform transmural blood flow in the absence of any stenosis. This beneficial transmural effect may resolve the paradox of why there is adrenergic coronary vasoconstriction during generalized sympathetic activation. The hypothesis is that the adrenergic vasoconstrictor mechanism has been adapted in the coronary circulation to help maintain subendocardial blood flow during exercise.

Human studies

$\alpha$-Receptor--mediated vasoconstriction. The intracoronary infusion of norepinephrine or phenylephrine in patients undergoing coronary artery bypass graft sur-
gery results in a prompt decrease in coronary blood flow, indicating small-vessel vasoconstriction. Normal segments of large coronary arteries in patients with angina exhibit 5% to 10% angiographic narrowing when α-receptor agonists are administered. These results are consistent with the animal studies cited above and demonstrate that large and small human coronary vessels respond to α-receptor agonists by constricting.

**Exercise.** There is a generalized sympathetic activation during exercise with tachycardia and an increase in blood pressure. In normal subjects, coronary blood flow always increases during exercise. The usual response to isometric handgrip or supine bicycle ergometer exercise in catheterized angina patients is also an increase in coronary blood flow. However, an interesting subset of patients with angina who developed angina during handgrip exercise had a decrease in coronary blood flow as measured with radioactive rubidium.

Handgrip or supine bicycle ergometer exercise has been shown by angiography to result in an active constriction of stenotic segments of coronary arteries, which produces a dramatic increase in the flow resistance of the stenosis. Constriction of the stenotic segment during exercise is prevented by nitroglycerin. A modest constriction during handgrip exercise has been observed in normal segments of large coronary arteries. The difference in response between normal arteries and stenotic segments may be due to the amplifying effect of atherosclerotic wall thickening. A small circumferential shortening of a thickened vessel will produce a very large change in lumen diameter, even if only a segment of the atherosclerotic vessel still has vascular smooth muscle in an eccentric lesion.

The hemodynamics of a critical stenosis are such that even a minute decrease in internal diameter causes the stenoses to become supercritical and severely limit flow. Because about 74% of human atherosclerotic lesions are eccentric with an arc of normal vessel wall, many patients are potentially at risk of worsening stenosis by adrenergic vasoconstriction.

Another possible mechanism for the difference in response between normal arteries and diseased segments is that endothelial cell function may be impaired in atherosclerotic segments so that vasodilation mediated via endothelium-derived relaxing factor is blunted, thereby unmasking adrenergic vasoconstriction.

**Cold pressor test.** Placing a subject’s hand in ice water elicits a reflex sympathetic response with a modest increase in blood pressure, heart rate, and peripheral resistance. Coronary blood flow has been measured with coronary sinus thermodilution during cold pressor tests, and in patients without significant coronary artery disease the expected increase in coronary blood flow secondary to the increase in myocardial metabolism is observed. Angiographic analysis of normal segments of arteries during a cold pressor test indicates there is a generalized vasoconstrictor response in large coronary arteries.

An interesting subset of patients with angina undergoing a cold pressor test manifests a decrease rather than an increase in coronary sinus blood flow. The region of decreased flow has even been localized to the region of atherosclerotic narrowing in some patients.

Administration of the α-receptor–blocking agent phentolamine blunts the coronary vasoconstriction in patients with angina. β-Receptor blockade with propranolol potentiates the cold pressor vasoconstrictor response. Although the cold pressor test can elicit spasm in some patients with variant angina, narrowing of coronary stenoses in patients not thought to have variant angina was observed in several cases.

Taken together, these studies suggest that placing a patient’s hand in ice water elicits a reflex α-receptor–mediated coronary vasoconstriction that in some patients results in supercritical narrowing of a stenotic arterial segment, which can lead to reduced flow despite tachycardia and an increase in blood pressure.

**α-Blockade.** Some patients with angina show an improved capability to exercise after α-receptor blockade. Of 12 patients not taking β-receptor–blocking agents, nine were able to exercise longer with phentolamine than with a placebo. The addition of the α1-receptor–blocking agent indoramin prolonged the time to angina during graded treadmill exercise in patients already taking β-blocking agents. The intracoronary infusion of phentolamine in patients undergoing cardiac catheterization lessened the degree of ST segment depression for a given heart rate during supine bicycle ergometer exercise. These results are consistent with an α-adrenergic mechanism that worsens angina during exercise.

Although α-receptor blockade may benefit some patients with angina, the peripheral vasodilating effect of α-blockade will lower blood pressure and may have an adverse effect in other patients. It has been demonstrated that at a given heart rate, lowering the aortic pressure is detrimental to the myocardium distal to a fixed stenosis even though lowering the afterload of the left ventricle diminishes myocardial oxygen consumption. This is because of the large pressure drop that occurs across a stenosis. In other words, the...
cost of decreasing the perfusion pressure across the stenosis is greater than the benefit of a reduced myocardial oxygen consumption.

The paradox and clinical implications

The paradox. Why is there an adrenergic coronary vasoconstrictor effect that restricts coronary metabolic hyperemia during generalized sympathetic activation? The answer appears to be that adrenergic vasoconstriction has been adapted in the coronary circulation to help maintain blood flow to the inner layers of the left ventricle during the tachycardia and functional hyperemia of exercise, emotion, and baroreceptor reflexes. An unexpected beneficial effect is that, in the presence of a fixed stenosis, adrenergic vasoconstriction in the outer layer of the left ventricle has a transmural antistole effect to preserve flow to the inner layer.

The hypothesis. Given that normal adrenergic vasoconstriction in large and small coronary vessels is beneficial, the hypothesis is that atherosclerotic narrowing complicates the situation so that the normal vasoconstrictor effect may be detrimental or beneficial (figure 1). "Normal" coronary vasoconstriction in an eccentric critical stenosis may make it become supercritical and severely limit flow. Conversely, normal adrenergic vasoconstriction of small vessels may have a beneficial anti-transmural steal effect.

Normal vasoconstriction vs coronary spasm. Although it has been suggested that adrenergic mechanisms are involved in coronary spasm of Prinzmetal's or variant angina, coronary spasm is not the topic of this essay. What is being considered here is normal adrenergic coronary vasoconstriction and how it may interact with atherosclerosis. Although coronary spasm may be elicited by adrenergic agents in some patients with variant angina,\textsuperscript{87-90} variant angina may also be triggered by other stimuli, including cholinergic agents\textsuperscript{89} and hyperventilation.\textsuperscript{91} Furthermore, the use of \(\alpha\)-receptor-blocking agents in patients with variant angina has been disappointing.\textsuperscript{92, 93} Although it is possible that variant angina represents the extreme end of the spectrum of adrenergic vasoconstriction, it seems unlikely at this time that coronary vasospasm is simply the result of norepinephrine acting on vascular \(\alpha\)-receptors in the usual manner.

Spasm implies some pathologic change in the mechanisms that lead to vascular constriction. There may be pathologic vasoconstrictor agents, altered receptor

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**FIGURE 1.** The hypothesis that adrenergic coronary vasoconstriction may interact with atherosclerosis in two ways is illustrated. (1) Adrenergic constriction of the "normal" segment of an epicardial coronary artery with an eccentric atherosclerotic lesion may severely worsen the stenosis. (2) Adrenergic vasoconstriction in the outer layers of the left ventricle distal to a stenosis may have an anti-transmural steal effect by preserving perfusion pressure for the vasodilated inner layer.
function, or augmented smooth muscle responsiveness. Until the mechanisms of variant angina are identified, it seems logical to consider variant and exertional angina separately rather than to combine them.

Caveats. For those who wish to evaluate the role of adrenergic vasoconstriction in clinical angina with adrenergic agonists, antagonists, denervation, and the like, it will be helpful to keep the following caveats in mind.

1. The dominant cause of exertional (not variant) angina is coronary artery stenosis. Adrenergic coronary vasoconstriction may alter the angina threshold up or down, but it is unlikely to be the primary cause.

2. The effects of adrenergic coronary vasoconstriction in patients with angina may be harmful or beneficial, depending on whether constriction in the stenotic segment or in the small vessels predominates. Vasoconstriction in the stenosis worsens the stenotic pressure gradient, whereas small-vessel vasoconstriction may have a beneficial anti-transmural steal effect.

3. Although the role of adrenergic constriction of coronary collateral vessels in angina appears to be untested thus far, collateral vasoconstriction is a possibility.

4. Peripheral adrenergic vasoconstriction during tachycardia is probably helpful for many patients with coronary stenoses, since an augmented arterial pressure increases the pressure gradient across the stenosis.

5. Atherosclerosis is a progressive disease (including collateral hypertrophy), and the harmful or beneficial effects of adrenergic vasoconstriction are unlikely to remain constant throughout the course of the patient's disease.

6. Resting sympathetic vasoconstrictor tone in the coronary circulation is probably low, so sympathetic discharge will need to be stimulated to study adrenergic effects.

7. Coronary spasm is probably different from normal adrenergic coronary vasoconstriction; therefore, including patients with variant angina in a study group is likely to add confusion.

Conclusion. Adrenergic vasoconstriction mediated via postjunctional \( \alpha_1 \)- and \( \alpha_2 \)-receptors acts primarily on small coronary vessels but also acts via \( \alpha_1 \)-receptors on large epicardial arteries. Adrenergic coronary vasoconstriction is a normal part of the generalized sympathetic activation that occurs during exercise, emotion, and baroreceptor reflexes. Normally this vasoconstriction limits the concomitant metabolic vasodilation and helps maintain blood flow to the inner layer of the left ventricle during tachycardia. In some patients with coronary atherosclerosis, the "normal" adrenergic vasoconstriction may further narrow the stenotic segment and be detrimental. In other patients with relatively fixed lesions, small-vessel vasoconstriction may produce a beneficial anti-transmural steal effect.

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