Background—Ischemia/reperfusion (I/R) injury complicates myocardial infarction and stroke by exacerbating tissue damage and increasing risk of mortality. We have recently identified C-type natriuretic peptide (CNP) as an endothelium-derived hyperpolarizing factor in the mesenteric resistance vasculature and described a novel signaling pathway involving activation of natriuretic peptide receptor C (NPR-C), which plays a pivotal role in the regulation of local blood flow. We tested the hypothesis that CNP/NPR-C signaling is a novel regulatory pathway governing coronary blood flow and protecting against I/R injury.

Methods and Results—CNP and (Cys18)-atrial natriuretic factor (4-23) amide (cANF4–23) elicited dose-dependent decreases in coronary perfusion pressure (CPP) that were blocked by Ba2+/H11001 and ouabain in the isolated Langendorff rat heart. The endothelium-dependent vasodilator acetylcholine elicited the release of CNP from the coronary endothelium. CNP and cANF4–23 reduced infarct size after 25 minutes of global ischemia and 120 minutes of reperfusion, maintaining CPP and left ventricular pressure at preischemic values. The vasorelaxant and protective activity of CNP and cANF4–23 were enhanced in the absence of endothelium-derived nitric oxide.

Conclusion—Endothelium-derived CNP is involved in the regulation of the coronary circulation, and NPR-C activation underlies the vasorelaxant activity of this peptide. Moreover, this newly defined pathway represents a protective mechanism against I/R injury and a novel target for therapeutic intervention in ischemic cardiovascular disorders. (Circulation. 2004;110:1231-1235.)

Key Words: endothelium-derived factors ■ myocardial infarction ■ natriuretic peptides ■ cardiovascular diseases ■ ischemia
Herein, we demonstrate that the CNP/NPR-C signaling pathway contributes to the regulation of blood flow and tissue perfusion in the coronary vasculature and that CNP is likely to represent a coronary EDHF. Moreover, we reveal that the CNP/NPR-C pathway exerts a potent protective effect against I/R injury and represents a novel target for the treatment of ischemic cardiovascular disorders.

Methods

Measurement of Coronary Hemodynamics and Cardiac Function
Male Wistar rats (260 to 340 g; Tuck, Rayleigh, UK) were surgically anesthetized with pentobarbital (45 mg/kg IP) and anticoagulated with heparin (1000 IU/kg IP). Hearts were excised and perfused retrogradely via the aorta, as previously described. Coronary perfusion pressure (CPP) and left ventricular developed pressure (LVDP) were continuously measured by inline pressure transducers (Becton Dickinson), as previously described. In some experiments, the vasodilator responses of CNP (10 nmol) and the selective NPR-C agonist (Cys18)-atrial natriuretic factor (4-23) amide (cANF4–23) (3 nmol) in the absence and presence of the NPR-C antagonist M37204912 (100 nmol/L, 15-minute pretreatment) were determined.

Bioassay of CNP
Effluent (60 mL) was collected before and during acetylcholine (ACh) application in hearts with an intact endothelium or after endothelium denudation (achieved by using 60 mg/L of 1% Triton X-100 delivered at 30 mL/min followed by a 20-minute recovery period); endothelial and smooth muscle integrity was tested before and after removal by using ACh (3 nmol) and sodium nitroprusside (10 nmol), respectively. Samples were concentrated on C18AR columns (DRG Diagnostics), and CNP concentrations were determined by using a commercially available radioimmunoassay (DRG Diagnostics) as previously described.

Effects of CNP on I/R Injury
After equilibration, hearts were treated with CNP (30 nmol/L), CNP plus M372049 (100 nmol/L), cANF4–23 (30 nmol/L), or saline vehicle (30 minutes) and then subjected to global ischemia (25 minutes) followed by reperfusion (120 minutes). In some experiments, CNP (30 nmol/L, 30 minutes) was administered only at the time of reperfusion. To identify infarcted tissue after I/R insult, hearts were cut into small pieces and incubated with p-nitroblue tetrazolium (0.5 mg/mL, 20 minutes at 37°C). Infarct size was expressed as a percentage of the dry weight of the infarcted areas over the total weight of the heart.

Data and Statistical Analysis
All data are expressed as mean±SEM, where n is the number of animals used. For comparison of single points, 1-way ANOVA was used, and for comparison of dose-response curves to CNP, 2-way ANOVA was used. Values were considered significantly different when P<0.05.

Results

Regulation of Coronary Perfusion by CNP/NPR-C Signaling
CNP (0.03 to 10 nmol) produced a dose-dependent decrease in CPP (median effective concentration, 9.47±0.71 nmol; E₉₀=3.81±0.29 mm Hg; n=4). The potency and maximal effect of CNP were significantly enhanced in the presence of L-NAME plus indomethacin but not altered in hearts perfused with the vasoconstrictor U46619 (1 μmol/L) to produce an equivalent increase in CPP (data not shown), and responses were attenuated in the presence of Ba²⁺ plus ouabain (Figure 1). The selective NPR-C agonist cANF4–23 also decreased CPP in a Ba²⁺ plus ouabain–sensitive manner (Figure 1, inset). The responses to both CNP and cANF4–23 were blocked by the selective NPR-C antagonist M372049 (Figure 1).

Release of CNP by the Coronary Vascular Endothelium
CNP concentrations in the effluent increased significantly after administration of ACh and mirrored the changes in CPP.
responses were absent after endothelial denudation (Figure 1; n=5).

CNP/NPR-C Signaling Protects Against I/R Injury

The I/R insult in control hearts produced an infarct of ~50% (Figure 2) and a concomitant increase in CPP and a reduction in LVDP (Figure 2). In the presence of CNP (during ischemia and reperfusion), CPP and LVDP were maintained at preischemic levels (Figure 2), with a significant reduction in infarct size that was more pronounced in hearts pretreated with L-NAME (Figure 2). In addition, in the presence of CNP, LVDP (85.9±12.4 mm Hg), −dP/dt (94.8±8.0 mm Hg/s), and left ventricular end-diastolic pressure (29.8±1.9 mm Hg) were significantly improved (ie, nearer to preischemic values) compared with controls (53.9±7.8 mm Hg, 80.2±7.4 mm Hg/s, and 49.8±1.9 mm Hg, respectively; P<0.05 for each, n=5) after 120 minutes of reperfusion. Infusion of CNP during reperfusion only also caused a significant reduction in I/R injury (Figure 2).

Similarly, cANF4−23 protected the heart from I/R injury, reducing infarct size and maintaining CPP and LVDP (Figure 2), an effect significantly enhanced in the presence of L-NAME. Moreover, M372049 attenuated the beneficial effects of CNP (Figure 2).

Discussion

We have recently described a novel signal transduction pathway in the vasculature involving endothelium-derived CNP, activation of NPR-C, and opening of a GIRK to bring about smooth muscle hyperpolarization and relaxation; such a pathway is likely to underlie the action of EDHF. In the present study, we have demonstrated that endothelial CNP also contributes to the regulation of coronary blood flow and, moreover, that the mechanism of action of CNP in the coronary vasculature occurs through an identical NPR-C coupling that we have characterized in the mesenteric vasculature. Not only is CNP/NPR-C signaling important in regulating coronary perfusion, but also its activation represents a protective mechanism against I/R injury by reducing infarct size and maintaining CPP and LVDP at preischemic levels. Thus, CNP/NPR-C signal transduction is likely to represent a widespread mechanism for the regulation of local blood flow and tissue perfusion and a novel therapeutic target for the treatment of ischemic cardiovascular disorders.

In isolated, perfused hearts, CNP elicited a potent, dose-dependent relaxation of coronary arteries, an effect blocked by treatment with Ba2+ plus ouabain, a combination of inhibitors that is generally accepted to block EDHF-dependent hyperpolarization. Moreover, the actions of CNP were mimicked by the selective NPR-C agonist cANF4−23, and the actions of both CNP and cANF4−23 were abolished by the selective NPR-C antagonist M37204912; such observations confirm that NPR-C activation underlies the vasorelaxant activity of CNP. Furthermore, the endothelium-dependent dilator ACh evoked the release of CNP into the coronary circulation. Together, these observations suggest that endothelium-derived CNP is likely to act as a coronary EDHF and to play a role in the regulation of blood flow in the coronary vasculature. This hypothesis is supported by previous publications indicating that CNP can mediate hyperpolarization of coronary arteries14 and that shear stress upregulates CNP expression in human endothelial cells. Interestingly, the vasoactivity of CNP was increased in the presence of NO synthase inhibition, in accord with previous observations made in endothelium-denuded coronary arteries and with the requirement for NO blockade to reveal EDHF bioactivity. This phenomenon implies complementary cytoprotective roles for CNP and NO in the coronary vasculature, whereby the loss of one pathway

Figure 2. A, Infarct size as percentage wet weight in isolated, perfused rat heart (Langendorff) subjected to 25 minutes of global ischemia followed by 120 minutes of reperfusion in presence and absence of CNP (3 nmol), cANF4−23 (3 nmol), L-NAME (300 μmol/L), and M372049 (100 nmol/L). B, CPP and C, LVDP in isolated, perfused rat heart (Langendorff) subjected to 25 minutes of global ischemia followed by 120 minutes of reperfusion in presence and absence of CNP (3 nmol) or cANF4−23 (3 nmol). *P<0.05 vs control, **P<0.05 vs CNP or cANF4−23 alone, ***P<0.05 vs CNP+L-NAME. n=5. All abbreviations are as defined in text.
might be compensated for by upregulation of the alternative system. This is of particular significance for ischemic cardiovascular disorders because they are characterized by loss of endothelium-derived NO bioactivity.\(^1\) Under such conditions, the influence of CNP/NPR-C may be heightened, and moreover, drugs mimicking the biological activity of CNP (ie, NPR-C agonists) may prove to be important new medicines to treat these diseases. This proposal is supported by the recent report that CNP release from the (coronary) endothelium is increased during cardiovascular disease.\(^9,\)\(^18\)

Having demonstrated the existence and vasorelaxant activity of a CNP/NPR-C transduction system in the coronary circulation, we performed further experiments to assess whether this novel signaling pathway represents a protective mechanism against I/R injury. Global ischemia followed by reperfusion produced a characteristic increase in CPP, a decrease in LDVP, and an associated area of infarction corresponding to \(\approx 50\%\) of total tissue weight. Treatment with either CNP (at concentrations comparable to that produced endogenously by the endothelium\(^8\)) or cANF\(^3\)–\(^4\) protected hearts against the damaging effects of I/R injury with suppression of both infract size and myocardial dysfunction. This protective effect was enhanced in the absence of endothelium-derived NO (ie, in the presence of L-NAME) but suppressed by NPR-C blockade with M372049. Moreover, administration of CNP during the reperfusion period alone also reduced I/R injury, suggesting that NPR-C activation may prove beneficial in patients presenting with an acute ischemic episode. Together, these data confirm that CNP/NPR-C represents a protective mechanism against I/R injury and add further weight to the importance of this newly defined transduction system in regulating cardiovascular homeostasis. Interestingly, several recent publications indicate that the bioactivity of EDHF is unaffected or actually upregulated after I/R injury.\(^19,\)\(^20\) perhaps linking the bioactivity of CNP as an EDHF with a protective mechanism limiting microvascular dysfunction.

The mechanism by which CNP/NPR-C exerts a protective effect against I/R injury remains unclear and merits further attention. Activation of NPR-C in the coronary vascular bed (as we have demonstrated in the mesenteric vasculature) results in the opening of a \(\mathrm{G}\) protein–gated \(\mathrm{K}_{\mathrm{IR}}\) current. Although responses to CNP were sensitive to \(\mathrm{Ba}^2+\). Reduced \(\mathrm{K}_{\mathrm{IR}}\) channel activity has been demonstrated previously to exacerbate I/R injury.\(^4\)–\(^8\) providing evidence that preserved activity of such channels, as would be achieved by NPR-C activation, is beneficial in minimizing I/R injury. Moreover, evidence accumulated in recent years provides considerable support for a common mechanism underlying the protective effect of several mediators (eg, NO, bradykinin, and adenosine) in I/R injury.\(^21\) Although the processes involved are far from clear, it is generally accepted that the opening of a \(\mathrm{K}_{\mathrm{ATP}}\) channel, either on the cytoplasmic and/or mitochondrial membrane, underlies the protective effects.\(^22\) Thus, the beneficial effect of CNP in I/R injury may be mediated via opening of a GIRK, which results in a similar change in net \(\mathrm{K}^+\) flux as that achieved by \(\mathrm{K}_{\mathrm{ATP}}\) channel opening. Alternatively, as the myocardial \(\mathrm{K}_{\mathrm{ATP}}\) channel belongs to the \(\mathrm{K}_{\mathrm{IR}}\) superfamily,\(^23,\)\(^24\) direct activation of the \(\mathrm{K}_{\mathrm{ATP}}\) channel by CNP cannot be excluded.

In sum, we have provided strong evidence that CNP modulates perfusion of the heart by activation of NPR-C and is likely to represent a coronary EDHF. We have also demonstrated that CNP/NPR-C signal transduction represents a novel protective mechanism against I/R injury. Such observations add considerable weight to the thesis that activation of NPR-C represents an important, cGMP-independent activity of CNP in the regulation of vascular tone. These actions, in combination with the protective effect of CNP/NPR-C in preventing I/R injury, highlight this signaling pathway as a novel therapeutic target to treat ischemic vascular disease (ie, myocardial infarction, stroke) and other cardiovascular disorders (eg, hypertension, atherosclerosis, restenosis).

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Natriuretic Peptide Receptor-C Regulates Coronary Blood Flow and Prevents Myocardial Ischemia/Reperfusion Injury: Novel Cardioprotective Role for Endothelium-Derived C-Type Natriuretic Peptide
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