C-type natriuretic peptide expression and pulmonary vasodilation in hypoxia-adapted rats

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C-type natriuretic peptide expression and pulmonary vasodilation in hypoxia-adapted rats. Am. J. Physiol. 275 (Lung Cell. Mol. Physiol. 19): L645–L652, 1998.—Atrial and brain natriuretic peptides (ANP and BNP, respectively) are potent pulmonary vasodilators that are upregulated in hypoxia-adapted rats and may protect against hypoxic pulmonary hypertension. To test the hypothesis that C-type natriuretic peptide (CNP) also modulates pulmonary vascular responses to hypoxia, we compared the vasodilator effect of CNP with that of ANP on pulmonary arterial rings, thoracic aortic rings, and isolated perfused lungs obtained from normoxic and hypoxia-adapted rats. We also measured CNP and ANP levels in heart, lung, brain, and plasma in normoxic and hypoxia-adapted rats.

Steady-state CNP mRNA levels were quantified in the same organs by relative RT-PCR. CNP was a less potent vasodilator than ANP in preconstricted thoracic aortic and pulmonary arterial rings and in isolated lungs from normoxic and hypoxia-adapted rats. We measured CNP and ANP levels in heart, lung, brain, and plasma in normoxic and hypoxia-adapted rats. We also measured CNP and ANP levels in brain tissue (30), CNP was originally thought to be a neurotransmitter expressed primarily in the central nervous system (18, 30). More recently, CNP has been found in tissues throughout the body including colon, lung, heart, and kidney (24). Although the physiological functions of the natriuretic peptides are not completely understood, all three compounds possess vasorelaxant and antiproliferative properties and appear to modulate vascular tone and remodeling primarily via particulate guanylate cyclase-linked receptors.

Despite structural similarity of CNP to the other natriuretic peptides, considerable evidence suggests that it plays a unique role in circulatory physiology. Whereas ANP and BNP are synthesized and secreted by the heart and interact primarily with the A-type particulate guanylate cyclase receptor, natriuretic peptide receptor-A (NPR-A) (19), CNP is expressed predominately in the central nervous system and in vascular endothelial cells (31, 32) and exerts its vasoactive effects via the B-type particulate guanylate cyclase receptor, natriuretic peptide receptor-B (NPR-B) (8). The distribution of NPR-A and NPR-B is such that CNP is less potent than ANP and BNP at increasing intracellular cGMP levels in vascular endothelial cells but is up to 10-fold more potent than ANP and BNP at increasing intracellular cGMP levels in vascular smooth muscle (27). In a study on anesthetized dogs (6), CNP had a greater effect on reducing blood pressure than ANP and little, if any, diuretic effect. Furthermore, CNP synthesis in vascular endothelial cells is markedly upregulated by transforming growth factor-β, one of the key growth factors involved in vascular remodeling (22), suggesting that CNP may act as a counterregulatory factor in vascular mitogenesis. Taken together, these findings suggest that unlike ANP and BNP, which appear to act in an endocrine fashion as cardiac hormones, CNP may act in a paracrine fashion to modulate vascular tone and remodeling.

Considerable evidence suggests that ANP and BNP help to mitigate the severity of pulmonary hypertension and right ventricular hypertrophy that develop during exposure to chronic hypoxia. Both peptides are potent pulmonary vasodilators (2, 10) and inhibit proliferation of vascular smooth muscle in vitro (1, 3, 12). Right ventricular expression and circulating levels of both peptides are elevated in hypoxia-adapted rats (10, 33), and continuous infusion of ANP during chronic hypoxia has been shown to blunt pulmonary hypertension, muscleization of peripheral pulmonary vessels, and right ventricular hypertrophy (14). Finally, ANP antibodies have been shown to worsen hypoxic pulmonary hypertension subacutely (13) and chronically (28). Moreover, preliminary studies on ANP-deficient
gene-targeted mice demonstrate higher right ventricular pressures and greater right ventricular mass under both normoxic and chronically hypoxic conditions than are found in mice with normal ANP expression (17).

The role of CNP in modulating pulmonary circulatory responses remains to be elucidated. In a preliminary study, Hill et al. (11) found that CNP was a less potent inhibitor of hypoxic pulmonary vasoconstriction in isolated perfused rat lungs than ANP. However, a more recent study (3) suggests that CNP is a more potent antiproliferative agent for rat pulmonary arterial smooth muscle cells. Plasma CNP levels are an order of magnitude lower than ANP levels (6, 32). However, because CNP is synthesized by pulmonary vascular endothelial cells, the concentration of CNP adjacent to pulmonary vascular smooth muscle may be higher than circulating CNP levels. Furthermore, steady-state mRNA levels of the functional CNP receptor NPR-B increase in the lungs during hypoxia (21). If this upregulation of gene expression is associated with higher NPR-B concentrations in pulmonary vascular smooth muscle, then the pulmonary vasodilatory effects of CNP could be potentiated during hypoxia.

The purpose of this study was to explore the potential role of CNP in modulating the pulmonary hypertensive response to hypoxia. We aimed to determine the pulmonary vasodilator potency of CNP relative to ANP and to determine whether the pulmonary vasodilator potency of CNP increases during chronic hypoxia. Furthermore, we hypothesized that if CNP helps to mitigate the development of hypoxic pulmonary hypertension, then circulating CNP levels and pulmonary CNP expression would increase during chronic hypoxia.

**METHODS**

Hypoxic exposure. Male Sprague-Dawley rats (Charles River Laboratory) weighing between 200 and 300 g were exposed to 3 wk of hypoxia with the use of hypobaric chambers (0.5 atm). Normoxic control animals were housed in identical cages adjacent to the hypobaric chambers. Cages were removed three times weekly for cleaning and replenishment of food and water. Rats were given standard rat chow and water ad libitum.

Isolated vessel studies. After anesthesia with pentobarbital sodium (100 mg/kg ip), rats underwent a median sternotomy and the heart and lungs were removed en bloc. The thoracic aorta and proximal intrapulmonary artery were carefully dissected out and cut into 2- to 3-mm rings. The rings were suspended between tungsten wires (32 µm) in a vessel bath containing Earle's balanced salt solution (Sigma, St. Louis, MO) at 37°C and aerated with 95% O2-5% CO2. The vessels were hung at tensions of 0.5 g for pulmonary arterial (PA) rings and 1.0 g for thoracic aortic (TA) rings. This has been shown to be optimal for active tension generation in a previous study. Vessels were tested for viability and intact endothelium by preconstriction with 10⁻⁶ M phenylephrine and demonstration of dose-dependent relaxation to acetylcholine. The baths were then flushed, and dose-response curves were performed with ANP and CNP (10⁻¹¹ to 10⁻⁶ M) in random order after the rings were preconstricted with phenylephrine (10⁻⁶ M). Parallel vessels were given an equal volume of saline at the same time points to serve as controls.

Vasodilation of isolated vessels is expressed as percent relaxation of maximal tension generated by phenylephrine.

Isolated lung studies. These studies were done to compare the effects of ANP and CNP on the acute pulmonary vasconstrictive response with hypoxia. Sustained hypoxic vasocstriction has been demonstrated in the isolated lung preparation but not in isolated vessels (29). Animals were anesthetized with ketamine (60 mg/kg im) and pentobarbital sodium (20 mg/kg ip). A cannula was inserted into the trachea, and the animal was ventilated with room air at a rate of 64 breaths/min with an inspiratory pressure of 9 cmH₂O and expiratory pressure of 2.5 cmH₂O. The chest was opened, and cannulas were placed in the PA and in the apex of the left ventricle. The heart and lungs were removed en bloc and perfused at 0.03 ml·min⁻¹·g body weight⁻¹ with heparinized blood collected from normoxic donor rats. Recirculated perfusate was maintained at 37°C, and lungs were then ventilated with 21% O₂-5% CO₂ at the same inspiratory and expiratory pressures described above. Blood gases and pH were monitored by taking samples from the venous effluent. The pH was maintained between 7.35 and 7.45 by adding bicarbonate or HCl. After a 20-min equilibration, lungs were injected with a bolus of angiotensin II (0.25 ng in 0.1 ml of saline) and then ventilated for 10-min periods of hypoxia (95% N₂-5% CO₂) alternating with 10-min periods of normoxia (21% O₂-5% CO₂). After three cycles of hypoxia-normoxia that were shown in preliminary studies to induce a maximal hypoxic pressor response, the lungs were made hypoxic and a dose response was done with either ANP, CNP, or saline. Dose-response curves to natriuretic peptides were constructed as previously described (10). Briefly, the PA cannula was injected with a 100-µl bolus containing 10⁻¹⁰ to 10⁻⁵ M concentrations of ANP or CNP in saline vehicle or 100 µl of saline alone. Injections were made after the vasodilator response of the previous dose of natriuretic peptide or saline had plateaued (in general, about every 3–5 min). The results were recorded as a percentage of the peak pressor response to hypoxia.

Measurements in intact animals. After 3 wk of hypoxia or normoxia (control), animals were anesthetized with ketamine (60 mg/kg im) and pentobarbital sodium (20 mg/kg ip). A catheter of V3 tubing (Biolabs, Lake Havasu City, AZ) was inserted into the right jugular vein and advanced into the right ventricle. Right ventricular systolic pressure was measured as the mean systolic pressure over 30 s. Another catheter was placed in the right carotid artery for measurement of mean arterial pressure. Blood (0.3 ml) was removed from the arterial catheter for measurement of hematocrit. Blood for CNP determination was obtained from the inferior vena cava via an abdominal incision. The heart, lungs, and brain were removed and dissected. The heart was separated into right and left atria, right ventricle (RV), and left ventricle plus interventricular septum (LV+S) for measurement of RV-to-body weight (RV/BW), LV+S weight-to-BW [(LV+S)/BW], and RV-to-(LV+S) weight (RV/LV+S) ratios. The right lung was used for CNP determination and RT-PCR. The left lung was dried at 40°C for 1 wk and reweighed for calculation of lung dry weight-to-body weight ratios (LDW/BW).

Determination of ANP and CNP levels. Blood was collected in chilled syringes with 1 mg/ml of EDTA and 500 kallikrein inhibitory units/ml of aprotinin, and plasma was separated by centrifugation at 4°C. Excised tissues were placed immediately in ice-cold Chomczynski-Sacchi reagent (3.68 M guanidine isothiocyanate, 0.016 M sarkosyl, 0.023 M sodium chloride, 0.18 M sodium acetate, and 0.96 M β-mercaptoethanol plus an equal volume of water-saturated phenol) and homogenized for 15 s at speed 6 with a Brinkmann homog-
RESULTS

Isolated vessel studies. The vasodilator potencies of ANP and CNP on preconstricted TA and PA rings are shown in Fig. 1. ANP was a slightly more potent vasodilator than CNP in TA and PA rings isolated from normoxic and hypoxia-adapted rats. Exposure to chronic hypoxia did not affect the vasodilator potencies of ANP and CNP on TA rings (Fig. 1A). There was a trend toward a decreased vasodilator effect of ANP and CNP on PA rings isolated from hypoxia-adapted rats compared with normoxic rats, but the differences did not reach significance (P = 0.09 and 0.21 for ANP and CNP, respectively; Fig. 1B).

Isolated lung studies. To determine the relative potencies of ANP and CNP on hypoxic pulmonary vasoconstriction, dose-relaxation curves were constructed for both peptides with the use of isolated intact lungs obtained from normoxic and hypoxia-adapted rats (Fig. 2). Acute hypoxia increased PA perfusion pressure from 12.2 ± 0.8 to 18.0 ± 0.6 mmHg in isolated lungs from normoxic rats and from 18.1 ± 0.9 to 21.1 ± 1.1 mmHg in lungs from hypoxia-adapted rats. The pulmonary pressor response to hypoxia was stable in normoxic and hypoxia-adapted lungs. Both ANP and CNP blunted hypoxic pulmonary vasoconstriction in isolated lungs obtained from normoxic rats, but ANP was more potent than CNP. At the maximum dose tested (10^{-6} mol), ANP completely reversed hypoxic pulmonary vasoconstriction, whereas CNP reduced peak PA pressure only ~30%. In isolated lungs obtained from hypoxia-adapted rats, ANP, but not CNP, blunted hypoxic pulmonary vasoconstriction. The vasodilator potencies of both ANP and CNP were less in hypoxia-adapted rat lungs than in lungs obtained from normoxic rats.

Cardiopulmonary responses to hypoxia. As shown in Table 1, rats exposed to 3 wk of hypoxia had lower body weights and higher hematocrits than normoxic rats.
There was no difference in mean systemic arterial blood pressure between the two groups, but, as anticipated, hypoxia-adapted rats had higher PA pressures than normoxic rats as evidenced by more than a twofold increase in right ventricular systolic pressure. The development of pulmonary hypertension in the hypoxia-adapted rats was accompanied by severe right ventricular hypertrophy. Right ventricular mass referenced either to body weight (RV/BW) or to LV+S [RV/(LV+S)] nearly doubled in hypoxia-adapted rats. There was also a trend toward slightly higher (LV+S)/BW in hypoxia-adapted rats, although the difference did not reach significance. This may have been related to the lower body weight compared with normoxic rats, as opposed to an actual increase in left ventricular mass. Hypoxic rats had higher LDW/BW values than normoxic rats, consistent with increased lung mass related in part to pulmonary vascular remodeling.

Plasma and tissue levels of CNP and ANP. Circulating CNP levels were within the range previously reported (6) and were 2.5 times higher in hypoxia-adapted rats than in normoxic control rats (15 ± 6 vs. 6 ± 1 pg/ml; P < 0.01). Figure 3 shows normoxic and hypoxic rat CNP and ANP levels normalized to tissue protein concentrations in the brain, right heart, and lung. In comparison to ANP, CNP levels in normoxic rats were approximately 30-fold higher in brain, 3-fold higher in lung, 50-fold lower in the right atrium, and nearly the same in the right ventricle. As reported previously, exposure to chronic hypoxia increased right ventricular ANP markedly (Fig. 3). There was a trend toward lower right atrial ANP levels in hypoxia-adapted rats, but the difference did not reach significance. Chronic hypoxia had little effect on ANP levels in the lung and brain. The effect of chronic hypoxia on tissue CNP content was most pronounced in lung where it fell nearly 75% (Fig. 3). This marked decrease could not be attributed to higher protein levels because hypoxia-adapted rat lung protein concentrations were not significantly greater than those from normoxic rats (11.9 ± 1.2 vs. 9.7 ± 1.1 µg/ml; P = 0.178). Exposure to chronic hypoxia also decreased right atrial CNP levels but had no effect on CNP concentrations in the right ventricle or brain (Fig. 3).

Steady-state CNP transcript levels. Because expression of the CNP gene in the lungs of normoxic and hypoxia-adapted rats could not be detected by Northern blot analysis, we measured steady-state CNP transcript levels by RT-PCR (Fig. 4). In concordance with tissue CNP concentrations, a greater degree of CNP gene expression was seen in the brain than in the right heart or lung. With the use of β-actin as an endogenous standard, right atrial CNP gene expression in hypoxia-
adapted rats was decreased compared with that in normoxic rats (Fig. 4), consistent with the finding of lower CNP levels (Fig. 3). No differences in CNP transcripts were detected between normoxic and hypoxia-adapted rats in the brain, right ventricle, or lung.

DISCUSSION

We had anticipated that the vasodilator potency of CNP would be increased in the pulmonary circulation of hypoxia-adapted rats because the genetic expression of the guanylate cyclase-linked receptor for CNP (NPR-B) is upregulated in the lung during hypoxia (21). However, we found no evidence to support this hypothesis. The vasodilator potency of CNP on PA rings from normoxic rats was slightly less than that of ANP and did not change significantly in hypoxia-adapted rats. Furthermore, CNP was a considerably less potent inhibitor of hypoxic pulmonary vasoconstriction than ANP in isolated perfused lungs from normoxic rats and had no detectable effect on hypoxic pulmonary vasoconstriction in isolated lungs from hypoxia-adapted rats. It is possible that the posttranscriptional rate of NPR-B expression is not enhanced during hypoxia despite the increase in steady-state mRNA levels. Alternatively, NPR-B expression may be increased elsewhere in the lung besides the pulmonary vascular bed, or hypoxia may decrease the responsiveness of NPR-B to CNP.

Our finding of a reduced pulmonary vasodilator effect of ANP in hypoxia-adapted animals conflicts with a previous study by Jin et al. (15), who reported that ANP caused a greater reduction in PA pressure in hypoxia-adapted rats than in normoxic control rats with the use of both intact animals and isolated lung preparations. However, Chen et al. (4) reported that ANP has less of a pulmonary vasodilator effect in hypoxia-adapted animals than in normoxic control animals. Furthermore, the studies both by Jin et al. (15) and Chen et al. (4) measured the effect of ANP on baseline perfusion pressure, as opposed to the present study in which we measured the ability of ANP to reverse hypoxic pulmonary vasoconstriction. Because the hypoxia-induced increase in PA perfusion pressure was only about one-half as great in hypoxia-adapted lungs as in normoxic lungs, it is possible that the reduced vasodilator effect of ANP in hypoxia-adapted lungs was due to lower pulmonary vascular tone rather than decreased responsiveness to ANP. Recently, ANP was shown to be less effective at reversing pulmonary pressor responses to the endoperoxide analog U-46619 in isolated lungs obtained from hypoxia-adapted vs. normoxic newborn piglets (26), consistent with the findings in our study. Regardless of the effect of chronic hypoxia on ANP vasodilator potency, our data show that CNP is a weaker pulmonary vasodilator than ANP in normoxic rats.
and hypoxia-adapted rats and argue against a role for CNP in protecting against hypoxic pulmonary vasoconstriction.

It is possible that CNP could act to blunt hypoxic pulmonary hypertension via other mechanisms such as inhibition of pulmonary vascular remodeling. In a recent study, Furaya et al. (9) demonstrated a pronounced antiproliferative effect of CNP in an in vivo model of carotid artery intimal thickening and found that the antiproliferative effect of CNP was more potent than that of ANP in systemic vascular smooth muscle cells. If CNP has a similar effect on pulmonary vascular smooth muscle, elevated levels of CNP in the plasma or pulmonary vascular tissue during chronic hypoxia could blunt pulmonary vascular remodeling.

In our study, circulating CNP levels were within the range previously reported (6) and rose two- to threefold during hypoxia, as we previously observed for both ANP and BNP (10). However, in contrast to the increase in right heart ANP and BNP synthesis that develops in the right ventricles of hypoxia-adapted rats (10, 33), we saw no evidence of increased CNP synthesis in the heart, lung, or brain after chronic hypoxia. In fact, CNP concentrations fell in the right atria and lungs of hypoxia-adapted rats compared with normoxic control rats. In an earlier study (23), a drop in right atrial ANP concentration during hypoxia was interpreted as increased ANP secretion, suggesting that the right atrium is an important source of increased plasma ANP levels during hypoxia. However, it is unlikely that the drop in right atrial and pulmonary CNP concentrations observed in the present study represents increased CNP synthesis by these organs or that these organs produce enough CNP to raise circulating levels. The baseline concentrations of CNP in the right atrium and lung were at least two orders of magnitude lower than right atrial ANP concentrations. Furthermore, unlike the high levels of right atrial ANP mRNA that are sustained throughout hypoxia (10, 33), CNP mRNA transcripts in the right atrium and lung could only be identified by RT-PCR amplification under normoxic conditions and fell lower or did not change during hypoxia. Because CNP expression was measured in whole lung homogenates rather than in pulmonary vascular endothelial cells, it is possible that an increase in CNP synthesis in the pulmonary endothelium was masked by a downregulation of CNP synthesis in other parts of the lung. However, in a preliminary study on cultured pulmonary microvascular endothelial cells, Nakashima et al. (25) found no increase in CNP levels in culture medium or cell lysates after exposure to hypoxia for up to 48 h.

In view of the lack of any discernible increase in CNP expression in the heart, lung, or brain, it is unlikely that the increase in plasma CNP levels in hypoxia-adapted rats was the result of increased CNP secretion. An alternative mechanism for the increase in circulating CNP levels may be a reduction in plasma CNP clearance. One of the primary routes of CNP elimination from the circulation is binding to the natriuretic peptide clearance receptor (NPR-C) followed by internalization and degradation of the peptide. Although clearance of CNP from the circulation has not been examined in hypoxia-adapted animals, Klinger et al. (16) have previously shown that the concentration of pulmonary NPR-C binding sites markedly decreases during hypoxia and that ANP clearance from the circulation is reduced. Other investigators (21) have shown a downregulation in steady-state NPR-C mRNA levels in the lungs of hypoxia-adapted rats. Because CNP and ANP have similar binding affinities for NPR-C, it is likely that the hypoxia-induced decrease in pulmonary NPR-C concentration slows pulmonary clearance of CNP from the circulation and contributes to elevated plasma CNP levels.

Although CNP was initially thought to be localized to the central nervous system and vascular endothelial cells, our finding of significant amounts of CNP in the heart and lungs is consistent with more recent reports (7, 24) of CNP mRNA transcripts in numerous organs, including colon, kidney, and heart. The presence of CNP in the heart and lungs is not related to cross-
reactivity with other natriuretic peptides because we found no cross-reactivity of the anti-CNP antibody used in this study with ANP or BNP, even at concentrations well above those found in these tissues. It is also unlikely that the isolation of CNP transcripts in the heart and lungs can be attributed solely to vascular endothelial cells within the organ. If the presence of CNP in the heart and lungs were limited to the vascular endothelium, we would have expected to find the greatest concentration of CNP in the lungs because of its greater endothelial cell surface. The fourfold higher concentration of CNP in the atria than in the lungs suggests that either CNP expression in the heart is not limited to the endothelium or the endothelial concentration of CNP is greater in the heart. In either event, our findings indicate that the atria may serve as sites of synthesis for circulating CNP that are downregulated during hypoxia.

Additional bands larger than the true CNP product were noted in some of the PCR reactions. Contamination of the reaction with genomic DNA was excluded by the lack of a PCR product in control lanes that contained RNA from the same samples that had not been reverse transcribed. It is possible that posttranscriptional processing of CNP results in multiple transcript sizes in some tissues.

In the present study, we found that CNP synthesis in the heart and lung is unchanged or reduced during hypoxia, whereas circulating CNP levels increase. The low circulating levels of CNP (2 orders of magnitude lower than ANP) under normoxic and hypoxic conditions suggest that circulating CNP is unlikely to play an important role in modulating pulmonary vascular tone relative to ANP. However, CNP levels in whole lung homogenates and in the systemic circulation may not reflect CNP activity in the pulmonary vascular bed. Recent studies (20, 31) suggest a paracrine role for CNP whereby it is synthesized and secreted in endothelial cells adjacent to vascular smooth muscle and then acts locally to inhibit vasoconstriction and vascular mitogenesis. Additional studies are needed to determine whether CNP expression in pulmonary vascular endothelial cells is augmented during chronic hypoxia in vivo. In the absence of such studies, our findings suggest that CNP plays a minor role compared with that of the other natriuretic peptides in protecting against the development of hypoxic pulmonary hypertension. Alternatively, it is possible that a hypoxia-related reduction in CNP synthesis in pulmonary vascular endothelial cells could lead to disinhibition of vascular smooth muscle growth (20) and thus be a contributing factor in the development of hypoxic pulmonary hypertension.

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REFERENCES


