ANP Differentially Modulates Marinobufagenin-Induced Sodium Pump Inhibition in Kidney and Aorta

Olga V. Fedorova, Natalia I. Agalakova, Christopher H. Morrell, Edward G. Lakatta, Alexei Y. Bagrov

Abstract—NaCl loading and plasma volume expansion stimulate 2 natriuretic systems, vasoconstrictor, digitalis-like Na/K-ATPase inhibitors and vasorelaxant ANP peptides. Several hormones, including ANP, regulate activity of the Na/K-ATPase by modulation of its phosphorylation state. We studied effects of ANP on Na/K-ATPase phosphorylation and inhibition by an endogenous sodium pump ligand, marinobufagenin, in the aorta and renal medulla from male Sprague-Dawley rats. Marinobufagenin dose-dependently inhibited the Na/K-ATPase in renal and vascular membranes at the level of higher (nanomolar) and lower affinity (micromolar) binding sites. Marinobufagenin (1 nmol/L) inhibited Na/K-ATPase in aortic sarcolemma (18%) and in renal medulla (19%). prepro-ANP 104 to 123 (ppANP) and α-human ANP ([α-hANP]) both 1 nmol/L) potentiated marinobufagenin-induced Na/K-ATPase inhibition in the kidney, but reversed the effect of marinobufagenin in the aorta. Similarly, ppANP and α-hANP modulated the sodium pump (ouabain-sensitive 86Rb uptake) inhibitory effects of marinobufagenin in the aorta and renal medulla. In renal medulla, ppANP and α-hANP induced α-1 Na/K-ATPase phosphorylation, whereas in aorta, both peptides dephosphorylated Na/K-ATPase. The effect of ppANP on Na/K-ATPase phosphorylation and inhibition was mimicked by a protein kinase G activator, 8-Br-PET-cGMP (10 μmol/L), and prevented by a protein kinase G inhibitor, KT5823 (60 nmol/L). Our results suggest that α-1 Na/K-ATPase inhibition by marinobufagenin in the kidney is enhanced via Na/K-ATPase phosphorylation by ANP, whereas in the aorta, ANP exerts an opposite effect. The concurrent production of a vasorelaxant, ANP, and a vasoconstrictor, marinobufagenin, potentiate each other’s natriuretic effects, but ANP peptides may offset the deleterious vasoconstrictor effect of marinobufagenin. (Hypertension. 2006;48:1160-1168.)

Key Words: sodium-potassium exchanging adenosinetriphosphatase ■ natriuretic hormones ■ ANP ■ ouabain ■ marinobufagenin ■ cGMP

The search for the identity of natriuretic factors that become activated under conditions of sodium retention and that promote natriuresis via inhibition of the Na/K-ATPase (NKA) in the renal tubules evolved from the concept of a natriuretic hormone.1–4 According to this concept, in hypertensive patients, excessive response of natriuretic systems is responsible for sodium retention and hypertension.3 Another group of endogenous natriuretic peptides, both exist in mammals. Members of the ANP family exhibit natriuretic effects and vasorelaxation,6,20 whereas MBG acts as a vasoconstrictor18 and inhibits renal NKA.9 Administration of anti-MBG antibody to rats with NaCl-sensitive hypertension lowers arterial pressure10,12 and reduces sodium excretion.11,19

Two humoral natriuretic systems, NKA inhibitors and natriuretic peptides, both exist in mammals. Members of the ANP family exhibit natriuretic effects and vasorelaxation,6,20 whereas MBG acts as a natriuretic and a vasoconstrictor.10,12 Both ANP21 and MBG10 become elevated in NaCl-sensitive volume-expanded hypertension. Recently, in hypertensive patients with congestive heart failure, we demonstrated that plasma levels of α-human ANP (α-hANP) and that of MBG exhibit a strong positive correlation.22

Based on the above observations, we hypothesized that simultaneous stimulation of ANP and MBG in NaCl-loaded volume-expanded states would potentiate each other’s natriuretic effects, whereas ANP would offset the potentially deleterious vasoconstrictor effect of MBG. Activation of the

Received October 26, 2005; first decision November 14, 2005; revision accepted September 21, 2006.
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Hypertension is available at http://www.hypertensionaha.org

DOI: 10.1161/01.HYP.0000248129.20524.d0
guanylyl cyclase–cGMP–protein kinase G (PKG) pathway underlies both renal and vascular effects of ANP peptides.23–26 Because cGMP has been reported to regulate activity of the NKA by modulation of its phosphorylation state,27,28 we also hypothesized that ANP would affect MBG sensitivity of the NKA via modulation of its PKG-dependent phosphorylation. Previously, ANP has been shown to inhibit renal sodium pump,25,29,30 and both direct and indirect evidence suggest that ANP and/or cGMP can stimulate the sodium pump in the cardiovascular system.24,31–33 We, therefore, further hypothesized that, whereas both ANP and MBG exhibit synergistic interaction on renal α-1 NKA, ANP would antagonize MBG-induced inhibition of the NKA in vascular sarcolemma.

Previous studies have shown that prepro-ANP (ppANP) becomes stimulated in patients with congestive heart failure24,35 and that, in vivo, in humans this peptide induces a natriuretic effect.35 In the present study, we compared the effects of α-1ANP and ppANP (H-Ser-Ser-Asp-Arg-Ser-Ala-Leu-Leu-Lys-Ser-Lys-Leu-Arg-Ala-Leu-Leu-Thr-Ala-Pro-Arg-OH; human ppANP 104 to 123, or pro-hANF 79 to 98, or kaliuretic peptide) on MBG-induced inhibition of the NKA and the sodium pump in rat aorta and renal medulla and studied effects of natriuretic peptides on phosphorylation of the NKA in these tissues.

Methods

Protocol

The protocol was approved by the Animal Care and Use Committee of the National Institute on Aging at the National Institutes of Health. Twenty-four Sprague Dawley rats (males, 8 to 10 weeks old; Charles River Laboratories, Wilmington, DE) and time-pregnant Sprague–Dawley rats at day 21 of gestation (n = 5; for preparation of NKA from fetal brain) were euthanized with an overdose of sodium pentobarbital (65 mg/kg, IP). Aortae and kidneys were collected and stored in liquid nitrogen (LN2).

Membranes from aortae were prepared as described previously.36 Aortic rings were minced by scissors, processed with Polytron 20S homogenizer (Kinematica) in 250 mmol/L of sucrose and 5 mmol/L of histidine solution (4°C; pH 7.4), and centrifuged (6000g; 15 minutes; 4°C) in a Sorvall RC-5B centrifuge (DuPont Instruments). The pellet was homogenized in a glass-Teflon homogenizer and combined with the supernatant, which was resuspended at 20 000g for 30 minutes at 4°C, and the resultant supernatant centrifuged (Beckman L8-N; 148 000g; 90 minutes; 4°C). The pellet was suspended in a homogenizing medium; applied to discontinuous sucrose gradients, consisting of 0.32, 0.8, 1.0, 1.2 and 1.4 mol/L layers buffered with histidine and 5 mmol/L of imidazole (pH 7.4), and centrifuged at 148 000g for 90 minutes (Beckman L8-N SW28; 4°C). The pellet appearing at the 0.8 mol/L fraction was aspirated, resuspended in a homogenizing medium to a protein concentration 3 to 4 mg/mL, and stored in LN2.

NKA from fetal brain, enriched in α-3 and α-2 NKA isoforms, was prepared as described previously with minor modifications.38 Brains were homogenized in a glass-Teflon homogenizer in a solution of 250 mmol/L of sucrose and 5 mmol/L of histidine (4°C; pH 7.4) and centrifuged (6000g; 15 minutes; 4°C) in a Sorvall RC-5B centrifuge (DuPont Instruments). The supernatant was centrifuged at 148 000g for 90 minutes at 4°C (Beckman L8-N; 148 000g; 90 minutes; 4°C). The resultant pellet was suspended in a homogenizing medium to a protein concentration of 2 mg/mL and stored in LN2.

NKA activity was measured as reported previously.36 To increase the permeability of membranes vesicles, membranes were pretreated with alamethicin (0.5 mg/mg of protein). Aliquots of aortic sarcolemma or renal medulla (1 μg protein/100 μL) were preincubated for 30 minutes at 37°C with compounds as described and then incubated for 1 hour (for aorta) or 15 minutes (for renal medulla) at 37°C in NUNC low-binding polystyrene plates in medium containing (in mM): NaCl 100, KCl 4, MgCl2 1, EDTA 1, Tris 50, ATP 3, and NaN3 5 (pH 7.4). The reaction was stopped by quenching solution containing 1.25 N H2SO4. NKA activity was estimated as the difference between total ATPase activity in the presence and absence of 5 mmol/L of ouabain. The NKA activity in aortic sarcolemma was 12.6±0.5 μmol of inorganic phosphate per milligram of protein per hour and comprised 15% of the total ATPase activity. The NKA activity in renal medulla was 28.6±0.9 μmol of inorganic phosphate per milligram of protein per hour and comprised 35% of the total ATPase activity.

NKA Phosphorylation

NKA phosphorylation was assessed as described previously.36,39 Membranes were pretreated with alamethicin (0.5 mg/mg of protein) and preincubated in the presence of compounds studied for 30 minutes at 32°C in a buffer containing (in mM): Tris phosphate 10, magnesium acetate 5, and CaCl2 0.5. Phosphorylation was initiated by the addition of [γ-32P]ATP (1000 counts per minute/pmol) to a final concentration of 70 μmol/L. The reaction was quenched with an equal volume of Novex Tri-Glycine SDS sample buffer. Electrophoresis was performed as described below (Western blotting). Phosphoproteins were visualized by a 12- to 24-hour exposure of nitrocellulose membranes on Kodak XAR-5 film at 4°C. The optical density of bands, corresponding to NKA (112 kDa), was quantified via laser densitometry using Bio-Rad Gel Doc 1000 software (Bio-Rad Laboratories). To verify the localization of α-1 NKA, the same nitrocellulose membranes were further exposed to the mouse monoclonal α-1 NKA antibody (Upstate Biotechnologies; 1:2000; Western blotting, below). Because basal levels of NKA phosphorylation in aortic sarcolemma were very low, phosphorylation has been enhanced by preincubation of membranes with 50 mmol/L phorbol 12,13-diacetate for 3 minutes before the addition of the studied compounds, as reported previously.36,40

Western Blotting

Solubilized protein from aortic sarcolemma, renal medulla, and fetal brain as a standard (where appropriate) was separated by 12% Tris-glycine polyacrylamide gel electrophoresis and transferred to a nitrocellulose membrane.26 The proteins were visualized using monoclonal mouse anti-α-1 NKA (Upstate Biotechnologies; Lake Placid, NY; 1:2000), polyclonal rabbit anti-α-2 NKA (Upstate Biotechnologies; 1:500), monoclonal mouse anti-α-3 NKA (Affinity BioReagents Inc, Golden, CO; 1:500) antibody, polyclonal rabbit anti-PKG1 (cGPK1β) antibody (Stressgen, Victoria, British Columbia, Canada; 1:2000), or polyclonal goat anti-PKG2 (cGKII) antibody (Santa Cruz Biotechnology, Inc, Santa Cruz, CA; 1:2500).
followed by incubation with peroxidase-conjugated anti-mouse or anti-rabbit antiserum (Amersham Corp; 1:1000) or anti-goat antiserum (Santa Cruz Biotechnology, Inc; 1:1000). NKA bands were visualized by 1- to 5-minute exposure of nitrocellulose membrane on Kodak XAR5 film.

**Sodium Pump in Aortic Rings**

The transport activity of sodium pump in the thoracic aorta was estimated by measurement of ouabain-sensitive $^{86}$Rb uptake, as reported previously. Vascular rings 2 to 2.5 mm in diameter were equilibrated for 60 minutes in 5-mL flasks in a medium containing (in mM): NaCl 120, KCl 4, CaCl$_2$ 2.5, MgCl$_2$ 2.0, NaH$_2$PO$_4$ 1.1, NaHCO$_3$ 24, and glucose 5.6 gassed with 95% O$_2$ and 5% CO$_2$ at 32°C (pH 7.4). Then $^{86}$Rb (0.1 Ci/sample; NEN Life Science Products) was added, and the vessels were incubated in the presence and in the absence of 2 mmol/L of ouabain for 60 minutes at 37°C. The aortic rings were then rinsed 3 times in ice-cold medium, blotted with filter paper, weighed, and counted in a gamma counter (Cherenkov radiation). Total $^{86}$Rb uptake was determined on a wet weight basis, and the activity of the sodium pump was estimated as the difference between the total uptake of $^{86}$Rb and the uptake in the presence of 2 mmol/L of ouabain and expressed in nanomoles of $^{86}$Rb per gram tissue per minute.

**Sodium Pump in Renal Medulla**

The activity of the sodium pump in the suspension of outer medullary tubules, in which fragments of the thick ascending limb comprise ~90% of tissue mass, was estimated by measurement of ouabain-sensitive $^{86}$Rb uptake as reported previously in detail. Slices of outer medulla were rinsed in ice-cold modified Eagle’s minimal essential medium, containing (in mM) NaCl 137, KCl 4, MgSO$_4$ 1, CaCl$_2$ 1, Na$_2$HPO$_4$ 0.33, NaHCO$_3$ 0.44, NaHCO$_3$ 4, glucose 5, essential and nonessential amino acids 4, and HEPES 15 (pH 7.4). Medullar fragments were incubated in the rinsing solution containing 0.1% collagenase (weight/volume; CLS 2; 215 U/mg; Worthington Biochemical Corp) and 0.1% BSA for 60 minutes at 37°C under aeration with 95% O$_2$–5% CO$_2$. The suspension of tubular fragments was then washed with ice-cold solution, resuspended in incubation medium to 2 to 4 mg of protein per milliliter, and preincubated at 32°C (pH 7.4). Then $^{86}$Rb (0.1 Ci/sample; NEN Life Science Products) for 10 minutes. Tubular $^{86}$Rb uptake was determined on a wet weight basis, and the activity of the sodium pump was estimated by measurement of ouabain-sensitive $^{86}$Rb uptake, as reported previously in detail. Slices of outer medulla were rinsed in ice-cold modified Eagle’s minimal essential medium, containing (in mM) NaCl 137, KCl 4, MgSO$_4$ 1, CaCl$_2$ 1, Na$_2$HPO$_4$ 0.33, NaHCO$_3$ 0.44, NaHCO$_3$ 4, glucose 5, essential and nonessential amino acids 4, and HEPES 15 (pH 7.4). Medullar fragments were incubated in the rinsing solution containing 0.1% collagenase (weight/volume; CLS 2; 215 U/mg; Worthington Biochemical Corp) and 0.1% BSA for 60 minutes at 37°C under aeration with 95% O$_2$–5% CO$_2$. The suspension of tubular fragments was then washed with ice-cold solution, resuspended in incubation medium to 2 to 4 mg of protein per milliliter, and preincubated at 37°C for 30 minutes. Then 200 µL of tubular fragments were then washed for 1 hour in oxygenated solution in the absence and presence of 5 mmol/L of ouabain. $^{86}$Rb uptake was determined after the addition of 10 µL of incubation solution containing 2 µCi of incubation solution containing $^{86}$RbCl (0.1 µCi/sample; NEN Life Science Products) for 10 minutes. Tubular fragments were then washed with ice-cold medium, centrifuged, and lysed in 1% sodium deoxycholate. The radioactivity was measured by liquid scintillation. Protein was measured by Lowry method. $^{86}$Rb uptake was expressed as nanomoles of $^{86}$Rb per milligram of protein per minute.

**Reagents**

MBG (99.5% purity) was purified from parotid glands of Bufo marinus toads as reported previously in detail. ppANP (104 to 123) was purchased from Bachem Bioscience Inc. α-ANP was purchased from Sigma Chemicals. A stable cGMP analog, 8-Br-PET-cGMP, and a PKG inhibitor, KT5823, were purchased from BioLog Life Science.

**Statistical Analyses**

Data are presented as mean±SEM. Statistical analyses used 2-way or 1-way ANOVA followed by multiple-comparisons Bonferroni test (GraphPad Instat and GraphPad Prism, GraphPad Software Inc) and by 3-way ANOVA (SAS 9.1).

**Results**

Figure 1 demonstrates the abundance of α-1, α-2, and α-3 NKA isoforms in aortic sarcolemma, in renal medulla, and in the reference membrane preparation, rat fetal brain. The α-1 NKA was abundant in the kidney and in aortic sarcolemma but was almost undetectable in fetal brain membranes. α-2 NKA was present in brain membranes, less in aortic sarcolemma, and was undetectable in the kidney. α-3 NKA was present in rat fetal brain membranes but was absent in renal medulla and in aortic sarcolemma.

Figure 2 presents concentration-response curves of MBG-induced inhibition of the sodium pump in aortic rings and in the suspension of outer medullary tubules (Figure 2A and 2B) and inhibition of the NKA in aortic sarcolemma and membranes from renal medulla (Figure 2C and 2D). The inhibitory effects of MBG were studied in the presence and the absence of a low concentration of ppANP (1 nmol/L). MBG potently, and in a concentration-dependent manner, inhibited the sodium pump and NKA from both tissues. In both tissues, inhibition occurred at the level of higher- and lower-affinity binding sites (Table). In aorta, ppANP markedly attenuated the NKA- and sodium pump-inhibitory effects of MBG at the level of high-affinity binding sites, and analysis of concentration-response curve revealed inhibition occurring at the level of low-affinity binding sites only (Table). The effects of ppANP on renal sodium pump and NKA were opposite of those in aorta, and ppANP potentiated sodium pump- and NKA-inhibitory effects of MBG. For example, whereas in the absence of ppANP 1 nmol/L MBG inhibited renal NKA by 19%, in its presence NKA became inhibited by 49%.

Using 3-way ANOVA (tissue, MBG concentration, and activity of NKA and sodium pump in the absence and in the presence of ppANP), we assessed the effect of tissue (aorta versus kidney) on the modulation of MBG-induced inhibition of the sodium pump and NKA by ppANP. The 3-way interaction term was very significant for both the sodium pump and NKA by ppANP. The effects of ppANP on renal sodium pump and NKA were opposite of those in aorta, and ppANP potentiated sodium pump- and NKA-inhibitory effects of MBG. For example, whereas in the absence of ppANP 1 nmol/L MBG inhibited renal NKA by 19%, in its presence NKA became inhibited by 49%.

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the sodium pump activity (CHISQ=892.03; PCHI<0.0001) and for NKA (CHISQ=574.08; PCHI<0.0001), indicating that ppANP differentially modifies the effect of MBG in the aorta and kidney.

Next, we studied the sodium pump inhibitory effect of 1 nmol/L MBG, a concentration that has been observed in plasma of hypertensive rats, in the presence of ppANP in the physiologically relevant concentration (1 nmol/L), a stable cGMP analog that activates PKG, 8-Br-PET-cGMP (10 μmol/L), and a PKG inhibitor, KT5823 (60 nmol/L). In aortic rings (Figure 3A), MBG alone inhibited sodium pump by 18%. A total of 1 nmol/L of ppANP did not affect aortic sodium pump activity, but in the presence of ppANP, MBG failed to induce sodium pump inhibition. Likewise, 8-Br-PET-cGMP fully antagonized MBG-induced sodium pump inhibition. A PKG inhibitor, KT5823 alone did not affect the sodium pump activity in rat aorta, but in the presence of KT5823 and ppANP, MBG inhibited sodium pump by 42%, that is, KT5823 not only reversed the effect of ppANP but also potentiated MBG-induced sodium pump inhibition.

In outer medullary tubules (Figure 3B), 1 nmol/L of MBG alone inhibited the sodium pump by 18%. A total of 1 nmol/L of ppANP alone had no significant effect on the sodium pump activity, but it markedly potentiated the sodium pump-inhibitory effect of 1 nmol/L of MBG. The effect of a PKG activator, 8-Br-PET-cGMP, in renal medulla was more substantial than that of ppANP; in its presence, MBG inhibited sodium pump by 45%. In the presence of KT5823, ppANP and MBG together did not affect sodium pump activity.

The reference compound ouabain (1 nmol/L) alone did not significantly alter the sodium pump activity in either aortic rings or outer medulla (Figure 3A and 3B). In both tissues studied, 1 nmol/L of ppANP did not alter the effects of ouabain (data not shown).

Data on the effect of ppANP on NKA phosphorylation are summarized in Figure 4. In renal medulla, 1 nmol/L of ppANP markedly enhanced NKA phosphorylation, and this effect was further potentiated by 8-Br-PET-cGMP, whereas a PKG inhibitor, KT5823, reduced ppANP-induced phosphorylation. The effects of ppANP on phosphorylation of aortic sarcolemma NKA were opposite from those in renal medulla. In aortic sarcolemma, ppANP reduced the level of NKA phosphorylation. 8-Br-PET-cGMP, a PKG activator, reduced NKA phosphorylation and potentiated ppANP-induced NKA dephosphorylation. A PKG inhibitor, KT5823, reversed ppANP-induced dephosphorylation of the NKA from aortic sarcolemma. As demonstrated in Figure 5, PKG 1 isoform was detected in the aorta, but not the kidney, whereas PKG 2 isoform was abundant in the kidney and undetectable in aorta.

### Table 1

<table>
<thead>
<tr>
<th>Compounds and Tissue</th>
<th>High-Affinity IC50 (nM)</th>
<th>Low-Affinity IC50 (μM)</th>
</tr>
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<tbody>
<tr>
<td>Sodium pump in aorta, ppANP (−)</td>
<td>1.6±0.4</td>
<td>13.9±3.8</td>
</tr>
<tr>
<td>Sodium pump in aorta, ppANP (+)</td>
<td>Undetectable</td>
<td>3.1±1.5</td>
</tr>
<tr>
<td>Sodium pump in renal medulla, ppANP (−)</td>
<td>1.4±1.8</td>
<td>23.9±6.9</td>
</tr>
<tr>
<td>Sodium pump in renal medulla, ppANP (+)</td>
<td>0.3±0.2</td>
<td>9.1±6.1</td>
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<tr>
<td>Na/K-ATPase from aorta, ppANP (−)</td>
<td>0.90±0.50</td>
<td>34±12</td>
</tr>
<tr>
<td>Na/K-ATPase from aorta, ppANP (+)</td>
<td>Undetectable</td>
<td>63±11</td>
</tr>
<tr>
<td>Renal Na/K-ATPase, ppANP (−)</td>
<td>1.1±4.1</td>
<td>20.0±2.5</td>
</tr>
<tr>
<td>Renal Na/K-ATPase, ppANP (+)</td>
<td>0.11±0.04</td>
<td>8.9±2.4</td>
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</table>

Data are means±SEM from 5–8 inhibitory curves. For individual analysis of concentration-effect curves for MBG: nonlinear regression using 2-site or 1-site competition models.
The main observations obtained with ppANP were confirmed using α-hANP at a concentration of 1 nmol/L (Figure 6). In rat aortic rings, α-hANP alone did not affect the sodium pump activity, but reversed sodium pump inhibition induced by 1 nmol/L of MBG (Figure 6A). In aortic sarcolemma, α-hANP stimulated NKA activity by 20% and also antagonized MBG-induced NKA inhibition (Figure 6B). Similar to ppANP, α-hANP reduced the level of phosphorylation of α-1 NKA from rat aortic sarcolemma (Figure 6C). In renal medulla, 1 nmol/L of α-hANP, unlike that of ppANP, alone inhibited the sodium pump and NKA (Figure 6D and 6E). However, 1 nmol/L of α-hANP potentiated inhibition of renal NKA and sodium pump by 1 nmol/L of MBG to a lesser extent than ppANP. Figure 6F demonstrates that 1 nmol/L of α-hANP potentiated phosphorylation of the NKA from renal medulla.

**Discussion**

The main findings of the present study are that ANP, via a cGMP-dependent mechanism, dephosphorylates NKA from vascular sarcolemma and markedly reduces its sensitivity to an endogenous digitalis-like ligand, MBG. In renal medulla, ANP exhibits an opposite effect, that is, it induces NKA phosphorylation and sensitizes the sodium pump to the inhibitory effect of MBG. Because aortic sarcolemma and renal medulla express PKG1 and PKG2 isoforms, respectively, we hypothesize that these 2 PKG isoforms mediate the opposing effects of ANP on NKA phosphorylation and MBG sensitivity.

Our present findings demonstrate that the inhibitory effect of low concentrations of MBG in renal NKA and sodium pump may be markedly enhanced by ppANP and by α-hANP. Thus, 1 nmol/L of MBG, a concentration that is present in plasma in hypertensive rats and in patients with congestive heart failure,\(^{10,22}\) inhibits renal sodium pump and NKA by \(\approx 20\%\). In the presence of a low concentration of ppANP, 1 nmol/L, the NKA-inhibitory effect of MBG becomes dramatically potentiated and achieves 49% (Figure 2B). Such a degree of inhibition in vivo should substantially influence renal sodium transport. In the present study, we investigated mechanisms of modulation of MBG-induced NKA/sodium pump inhibition using ppANP at the concentration 1 nmol/L. Plasma levels of this peptide in healthy individuals comprise \(\approx 0.1\) nmol/L.\(^{34,35}\) In patients with congestive heart failure, plasma concentrations of ppANP exceed 1 nmol/L.\(^{35}\) Previously, in the kidney, physiologically relevant concentrations of this peptide have been shown to act via a guanylyl-cyclase/cAMP-dependent mechanism and to inhibit renal NKA.\(^{23,29}\)

Clinical data demonstrate that after administration to patients, ppANP exhibits high natriuretic activity but does not significantly affect the arterial pressure.\(^{35}\) In humans, α-hANP lowers the blood pressure\(^{20}\) but produces a more modest natriuretic effect as compared with that of ppANP.\(^{35}\) This pattern is consistent with a pattern of modulation of MBG-induced inhibition of the NKA by 2 natriuretic hormones observed in the present study (Figures 2D and 6B): whereas ppANP more potently potentiated MBG-induced inhibition of NKA from renal medulla, α-hANP more potently reversed MBG-induced inhibition of NKA from aortic sarcolemma. However, in the \(^{86}\)Rb transport experiments performed in aortic rings and in medullary tubular fragments, potency of ppANP and α-hANP did not differ with respect to

**Figure 3.** The sodium pump inhibition by 1 nmol/L of MBG in the absence and in the presence of 1 nmol/L of ppANP, 10 μmol/L of 8-Br-PET-cGMP (PET), 60 nmol/L of KT5823 (KT), and their combinations in the rings of rat aorta and in outer medulla. Ouabain ([OU] 1 nmol/L) has been tested as reference compound. Each bar represents the mean ± SEM of 6 to 12 measurements. By 1-way ANOVA followed by Bonferroni test: *P<0.01 vs control; #P<0.01 vs effect of MBG alone; @P<0.01 vs combined effect of MBG and ppANP. By 2-way ANOVA: Effect of MBG in renal medulla in the absence and in the presence of ppANP (MBG: P<0.001; ppANP: P<0.001; interaction: P=0.03); effect of MBG in renal medulla in the presence and in the absence of PET (MBG: P<0.001; PET: P<0.001; interaction: P=0.01); effect of MBG and ppANP together in the absence and in the presence of KT in renal medulla (MBG and ppANP: P<0.001; KT: P<0.014; interaction: P=0.01). Effect of MBG in aorta in the absence and in the presence of ppANP (MBG: P<0.01; ppANP: P<0.02; interaction: P=0.001); effect of MBG in aorta in the presence and in the absence of PET (MBG: P<0.02; PET: P<0.001; interaction: P=0.001); and effect of MBG and ppANP together in the absence and in the presence of KT in aorta (MBG and ppANP: P<0.001; KT: P<0.005; interaction: P=0.006).
modulation of MBG-induced inhibition of the sodium pump (Figures 3A, 3B, 6A, and 6D). We hypothesize that biologically active compounds known to affect the NKA activity and produced by renotubular, vascular, and endothelial cells (endothelin-1, angiotensin II, and NO)16 might have interacted with the effects of natriuretic peptides. Further studies of NKA modulation by ANP are required to explain the above difference in potency.

Previous studies demonstrated the importance of regulation of renotubular NKA by protein kinases with regard to fine tuning of the mechanisms controlling renal sodium excretion.30,44 Stimulation of vascular NKA as a consequence of the cGMP–PKG pathway activation has been described in previous experiments.24,31–33 Our present results demonstrate that the effects of both ppANP and a stable cGMP analog, 8-Br-PET-cGMP, are associated with a dephosphorylation of α-1 NKA from aortic sarcolemma and with a loss of its sensitivity to an endogenous ligand, MBG. In the present experiment, a PKG inhibitor, KT5823, partially reversed ppANP-induced dephosphorylation of the NKA from aortic sarcolemma, but the level of phosphorylation remained reduced (Figure 4D). Nevertheless, the inhibitory effect of MBG on the sodium pump in aortic rings in the presence of both ppANP and KT5823 was augmented (Figure 3A). This observation suggests that other factors, such as protein kinase A and protein phosphatases,25,27,30 may be involved in the regulation of NKA phosphorylation by ANP.

The mechanisms underlying the effect of PKG on the levels of NKA phosphorylation have been investigated in several previous studies. Blanco et al27 have shown that α-NKA isoforms differentially respond to PKG activation: whereas cGMP inhibited activity of α1/β1 and α3/β1 isozymes, it did not affect the activity of α2/β1. Subsequently, it was demonstrated that PKG phosphorylates α-isof orm of the NKA from various species.28 In this study, unlike phosphorylation sites for protein kinases A and C, located in the NKA α-subunit C and A terminus, respectively, the site for PKG phosphorylation was found to be located in the central part of the α-subunit polypeptide chain. The above results28 agree with the earlier data of Scavone et al,25 who demonstrated that low ANP concentrations, via a cGMP-dependent mechanism, inhibit the NKA from rat renal medulla. Because this cGMP-dependent effect has been mimicked by a protein phosphatase inhibitor, okadaic acid, it has been concluded that NKA phosphorylation is a potential target for cGMP-dependent effects of ANP.25 More recently, in rabbit cardiomyocytes,
sodium nitroprusside was shown to stimulate the sodium pump, but, unlike the above results obtained by Scavone et al., okadaic acid in this experiment abolished, rather than potentiated, cGMP-dependent sodium pump stimulation. Studies of the impact of PKG isoforms on its opposing effects on the NKA are required to elucidate the mechanism of action of PKG on the sodium pump activity and phosphorylation status.

In conclusion, our results demonstrate that α-1 NKA inhibition by MBG is enhanced via NKA phosphorylation by ANP in the kidney, whereas in the aorta, ANP exerts an opposite effect. Thus, the concurrent production of a vasorelaxant ANP and a vasoconstrictor, MBG, may potentiate each other’s natriuretic effects, but ANP peptides can offset the deleterious vasoconstrictor effect of MBG.

**Perspectives**

Our present observations may have pathophysiological implications. Under conditions of sodium loading and fluid retention, when both MBG and ANP peptides are stimulated, ANP would potentiate an MBG-induced adaptive natriuretic effect but would offset its maladaptive action, vasoconstriction. Aging, hypertension, diabetes mellitus, and congestive heart failure are all associated with heightened levels of digitalis-like sodium pump ligands and with a decline in cGMP-PKG signaling in the kidney and cardiovascular tissues. Such a decline may shift the balance between effects of MBG and ANP on renal and cardiovascular NKA toward lesser inhibition of renal sodium pump and greater inhibition of vascular NKA and, thus, contribute to the pathogenesis of hypertension. In accord with the above notion, blockade of elevated levels of circulating MBG with a specific anti-MBG antibody produces antihypertensive effects in NaCl-loaded Dahl-S rats, pregnant rats with preeclampsia-like symptoms, and hypertension in chronic renal failure. All the above conditions are associated with the impairment of protective endothelial cGMP-dependent mechanisms. Moreover, recent evidence indicates that nanomolar MBG concentrations stimulate generation of reactive oxygen species and induce hypertrophic signaling and fibrosis in cardiomyocytes. Therefore, ANP could also counterbalance growth-promoting effects of NKA inhibitors, in agreement with the growing evidence of tissue-protective effects of ANP peptides.

**Acknowledgments**

We gratefully acknowledge critical comments of David E. Anderson, PhD (National Institute on Aging, National Institutes of Health) and
are grateful for excellent technical assistance by Danielle Joseph and Alexandra Namikas.

Source of Funding
This study has been supported by the Intramural Research Program, National Institute on Aging, National Institutes of Health.

Disclosures
None.

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Hypertension. 2006;48:1160-1168; originally published online October 16, 2006; doi: 10.1161/01.HYP.0000248129.20524.d0
Hypertension is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0194-911X. Online ISSN: 1524-4563

The online version of this article, along with updated information and services, is located on the World Wide Web at:
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