Low Sodium Modifies the Vascular Effects of Angiotensin-CONverting Enzyme Inhibitor Therapy in Healthy Rats

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Received February 19, 2004; accepted June 2, 2004

ABSTRACT

Low dietary sodium (LS) increases the effect of angiotensin-converting enzyme (ACE) inhibitor therapy in patients and experimental models, but mechanisms underlying this enhanced efficacy are largely unknown. Because the benefits of ACE inhibition are mediated to a considerable extent by their effect on the vasculature, we studied whether low sodium alters the vascular effects of ACE inhibition. Baseline functional and morphological characteristics, and endothelium-dependent and -independent dilatory responses were studied in isolated perfused small intrarenal and mesenteric arteries obtained from control rats (CON), rats on LS, lisinopril-treated rats (CON-LIS), or rats treated with lisinopril during LS (LS-LIS). We found, first, that LS-LIS compared with CON-LIS enhances blood pressure reduction. Second, interlobar renal arteries had increased lumen diameter and reduced adrenergic contractility in CON-LIS compared with CON, without additional effects of LS. In contrast, mesenteric arteries were not altered in CON-LIS compared with CON, but became triggered for increased myogenic and adrenergic constriction in LS-LIS. Third, LS-LIS decreased acetylcholine (ACh)-induced vasodilation in both mesenteric and renal arteries compared with CON-LIS. During the latter condition, opposite prostaglandins are involved in the endothelial function of the two different vascular beds, i.e., increased involvement of contractile prostaglandins in ACh-induced vasodilation in renal arteries, versus dilatory prostaglandins in mesenteric arteries. Whether cause or consequence of the enhanced blood pressure response, our data demonstrate a modifying effect of dietary sodium on vascular effects of ACE inhibition. These findings provide a rationale for further studies addressing the mechanism-of-actions of our therapies to find additional strategies to improve therapy response.

Intervention in the renin-angiotensin system (RAS) by angiotensin-converting enzyme (ACE) inhibitors has proven to be an effective strategy to improve renal and cardiovascular prognosis in different patient populations. The response to ACE inhibition is modified by sodium intake, with a blunted response during high sodium intake, and an enhanced response during dietary sodium restriction. This occurs irrespective of the underlying disorder and applies to the effect on blood pressure, renal hemodynamic response, and proteinuria (Heeg et al., 1989; Teravainen et al., 1997; Buter et al., 1998), in experimental conditions and as well as in humans (Navis et al., 1987; Wapstra et al., 1996; Wing et al., 1998). Although ACE inhibitors have been studied extensively, the mechanism of the modifying effect of sodium intake on their efficacy is not well understood. The effects of ACE inhibition are believed to result from their hemodynamic actions, as well as from pressure-dependent and -independent effect on the vessel wall. In this respect, many studies showed improved vessel wall structure and dimension, and improved endothelial function in cardiovascular disease after chronic ACE inhibitor therapy (Mancini, 2000). We hypothesized that dietary sodium intake modifies the vascular effects of maintenance treatment with ACE inhibitors.

To address this hypothesis, isolated perfused preparations of small intrarenal and mesenteric rat artery were studied for baseline functional and morphological vessel characteristics, and endothelium-dependent and -independent dilatory responses after maintenance treatment with lisinopril with or without low dietary sodium. Because the heterogeneity of the vascular bed is well established, we studied two different
vascular beds. Small renal interlobar arteries were studied because of the importance of the kidney as a target organ for ACE inhibition (Wing et al., 1998). In addition, small mesenteric arteries were studied because of the importance of this artery type in the regulation of total peripheral vascular resistance.

Materials and Methods

**Rat Studies.** Male Wistar rats (250–300 g; Harlan, Zeist, The Netherlands) were housed under standard conditions at the animal facility of the University of Groningen and studied in accord with institutional and legislator regulations. After an adaptation period of 1 week, rats were allocated to one of four experimental groups (n = 8–10/group) receiving different treatments. The ACE inhibitor lisinopril (LIS, 75 mg/l) was given for a period of 3 weeks via tap water to rats either fed a control diet (Hope Farms, Woerden, The Netherlands) with modestly elevated sodium (CON-LIS, 2.0% NaCl) or a low sodium diet (LS-LIS, 0.05% NaCl), and comparisons were made to rats treated with vehicle (CON (2.0% NaCl) and LS (0.05% NaCl), respectively). Once per week, rats were put in metabolic cages for collection of 24-h urine samples and routine analyses of urinary sodium content. After prior training sessions to get accustomed with the experimental setup, systolic blood pressure was determined in conscious animals at the end of the treatment period by means of the tail-cuff method using an automated multichannel system (Life Science, Woodland Hills, CA); a mean of three subsequent recordings was taken as the final value.

At sacrifice after 3 weeks of treatment, rats were anesthetized with 1.5% isoflurane in N2O/O2, and blood samples were taken for determination of plasma ACE activity, i.e., hippuryl-his-leu cleavage with 1.5% isoflurane in N2O/O2, and blood samples were taken for determination of plasma ACE activity, i.e., hippuryl-his-leu cleavage method as described previously by Hirsch et al. (1991). Intestines and kidneys were removed and put into cold Krebs’ solution. Third-order branches of the superior mesenteric artery and renal interlobar arteries of the right kidney were isolated from surrounding perivascular tissue in cold Krebs’ buffer solution.

**Vascular Studies.** Small renal interlobar arteries and small mesenteric arteries were transferred to an arteriograph system for pressurized arteries (Living System Instrumentation, Burlington, VT) (Halpern et al., 1984). Artery segments were cannulated at both ends on glass micropipettes, secured, and the lumen of the vessel was filled with Krebs’ solution through the micropipettes as described previously (Gschwend et al., 2002). Intraluminal pressure was set to 70 mm Hg and held constant (blind sac) by a pressure servo system (Living System Instrumentation). The vessel chamber was continuously recirculated with warmed (37°C) and oxygenated (5% CO2 in O2) Krebs’ solution with a pH of 7.4. The vessel chamber was transferred to the stage of an inverted light microscope with a videocamera attached to a viewing tube. The video dimension analyzer (Living System Instrumentation) was used to analyze the signal obtained from the video image and to continuously register lumen diameter and wall thickness. Arteries were followed for development of myogenic tone at 70 mm Hg and allowed to equilibrate for 1 h in regular Krebs’ solution before being preconstricted with phenylephrine (PE) (Gschwend et al., 2003).

Initially, vessels were all stimulated with a fixed dose of PE (3 × 10^-7 mol/l), and the level of contraction was assessed. Thereafter, because this resulted in different contraction levels, the concentration of PE was slowly increased (varying from 3 × 10^-7 to 3 × 10^-6 mol/l) to finally obtain similar levels of preconstriction (diameter reduction by 40 ± 2% in mesenteric arteries and by 37 ± 1% in renal arteries). Preconstricted vessels were then studied for endothelium-dependent relaxation by giving cumulative doses of acetylcholine (ACh; 10^-8–10^-4 mol/l) to the recirculating bath. To determine the contribution of vasoactive prostaglandins (PGs), the response to ACh was additionally studied as in the above but now in presence of the cyclooxygenase (COX) inhibitor indomethacin (10^-3 mol/l) added to the organ bath 20 min before addition of ACh.

In a limited number of the arteries (n = 4 for each group), after endothelial function measurements, additional concentration-response curves to sodium nitroprusside (SNP, 10^-8–3 × 10^-4 mol/l) were obtained in preconstricted arteries to account for dilatative ability of arterial smooth muscle to nitric oxide.

**Solutions and Drugs.** Rats were treated with lisinopril supplied by Merck Sharp and Dohme Research Laboratories (Rahway, NJ). Vessel segments were superfused with Krebs’ solution containing 120.4 mmol/l NaCl, 5.9 mmol/l KCl, 2.5 mmol/l CaCl2, 1.2 mmol/l MgSO4, 25.0 mmol/l NaHCO3, 1.2 mmol/l NaH2PO4, and 11.5 mmol/l glucose (Merck, Darmstadt, Germany). Acetylsalicylic chloride, L-phenylephrine hydrochloride, sodium nitroprusside dihydrate, and indomethacin were obtained from Sigma-Aldrich Chemie B.V. (Zwijndrecht, The Netherlands). They were dissolved in deionized water and diluted with Krebs’ solution. Stock solution (10^-3 mol/l) for indomethacin was prepared in 96% ethanol (<0.1% final organ bath concentration).

**Data Analysis.** Myogenic constriction was expressed as a percentage of constriction = 100 × [(Dbase – Dmyo)/Dbase], where D is the diameter before the development of myogenic tone (Dbase) or the diameter after the development of myogenic tone (Dmyo). Concentration-response curves to ACh and maximal relaxation (Emax) were expressed in percentage of preconstriction to PE. The area under each individual curve (AUC) was determined (Sigma Plot; SPSS Inc., Chicago, IL) and expressed in arbitrary units. The AUC was used to present total (individual) ACh dilation, and for subsequent analysis of differences in ACh dilation with and without indomethacin (Buikema et al., 2000). Data are expressed as mean ± S.E.M. Group comparison was performed using one-way ANOVA, or repeated measures ANOVA in case of full concentration-response curves to ACh and SNP, and when appropriate corrected for multiple comparison by Duncan’s multiple range test. Statistical differences were determined using Student’s paired or unpaired t test, where appropriate. Significance was accepted at P < 0.05.

**Results**

**Rat Characteristics.** In conjunction with their diets, urinary sodium excretion was significantly higher in control rats (CON) than in low sodium-fed rats (LS), and this was most pronounced in control rats treated with lisinopril (CON-LIS) (Table 1). Dietary sodium restriction per se did not

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**Table 1**

| Rat characteristics after treatment for 3 weeks on a control diet (CON, 2.0% NaCl), a low sodium diet (LS, 0.05% NaCl), treated either with vehicle, or the ACE inhibitor LIS (75 mg/l drinking water). Data are mean ± S.E.M. of n = 8 to 10 observations in all cases. |
|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | CON-LIS         | LS              | LS-LIS          |
| Urinary sodium (mg/d) | 3.3 ± 0.3       | 4.9 ± 0.4*      | 0.66 ± 0.1*     | 0.54 ± 0.1†     |
| Body weight (g)       | 398 ± 10        | 398 ± 11        | 398 ± 12        | 312 ± 5*        |
| Systolic blood pressure (mm Hg) | 140 ± 4        | 125 ± 4*        | 143 ± 6         | 102 ± 2*†       |
| Plasma ACE activity (His-Leu nM/ml/min) | 75 ± 7        | 30 ± 2*         | 68 ± 6          | 23 ± 4*         |

* P < 0.05 for CON-LIS versus CON or LS-LIS versus LS.
† P < 0.05 for LS versus CON and LS-LIS versus CON-LIS.
affect rat body weight and systolic blood pressure in these healthy animals, which is in accordance with the normal functioning of regulatory mechanisms of the renal-body fluid system for arterial pressure control. The effect of lisinopril on plasma ACE activity was comparable in both sodium groups. A significant reduction in body weight was observed only after treatment with lisinopril during low sodium intake. As anticipated, the reduction in systolic blood pressure after treatment with lisinopril was significantly more pronounced during low sodium intake compared with control, demonstrating the enhanced therapeutic efficacy of ACE inhibition during dietary sodium restriction.

Apart from urinary sodium excretion, the low dietary sodium per se compared with the control diet had no significant effect on the parameters in Table 1, or on those investigated in the following sections. Therefore, for reasons of conciseness, the data from the low dietary sodium group were not presented hereafter.

**Baseline Vessel Characteristics.** Dietary sodium restriction per se had no significant effects on baseline morphological and functional vascular properties in mesenteric resistance arteries and renal interlobar arteries (data not shown).

After treatment with lisinopril, renal arteries showed significantly increased lumen diameter at baseline and decreased PE-induced constriction. The effects were similar during both sodium regimens, i.e., the ACE inhibitor effect was not modified by dietary sodium restriction (Table 2).

In contrast to the renal arteries, baseline characteristics of mesenteric arteries were not affected by treatment with lisinopril. In combination with dietary sodium restriction, however, mesenteric arteries showed significantly increased myogenic tone development and increased PE-induced constriction (Table 2).

The contribution of prostaglandins in the contractile response to PE in the two vascular beds is shown in Fig. 1. In renal arteries, incubation with indomethacin similarly reduced PE-induced constriction in all groups in such a way that lisinopril-induced group differences persisted; hence, lisinopril-induced effects on PE-induced constriction persisted in presence of prostaglandin inhibition (Fig. 1A). In mesenteric arteries, presence of indomethacin reduced PE-induced constriction in all groups. This effect was most pronounced in LS-LIS, in which PE-induced constriction was profoundly increased compared with the other groups (Fig. 1B).

**ACh Induced Dilation and the Contribution of Prostaglandins.** Full concentration-response curves to ACh and SNP in absence of indomethacin are given for individual groups in Fig. 2. Endothelium-independent dilation to SNP did not differ between the groups, neither for mesenteric nor for renal arteries, implying that potential alterations at the level of vascular smooth muscle cell reactivity do not account for possible group differences in ACh-induced dilation.

The contribution of PGs to total ACh induced dilation was calculated as differences in the AUCs for ACh-induced dilation in absence and presence of indomethacin for individual groups. These data are shown in Fig. 3. In renal arteries, ACh induced dilation was not altered by lisinopril per se or by dietary sodium (data not shown). However, the combination of lisinopril and low sodium reduced the ACh induced dilation to approximately one-third (Fig. 2A). Incubation with indomethacin had no effect in CON and CON-LIS but partly restored vasodilation in LS-LIS (Fig.

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**TABLE 2**

Rat vessel characteristics after treatment for 3 weeks on a control diet (CON, 2.0% NaCl), a low sodium diet (LS, 0.05% NaCl), treated either with vehicle or the ACE inhibitor LIS (75 mg/l drinking water). Myogenic and PE (phenylephrine, 3 × 10⁻⁶ mol/L)-induced tone are expressed as percentage of constriction from baseline. Data are mean ± S.E.M. of n = 8 to 10 observations in all cases.

<table>
<thead>
<tr>
<th>Vessel characteristics</th>
<th>CON</th>
<th>CON-LIS</th>
<th>LS-LIS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Renal arteries</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter (μm)</td>
<td>296 ± 8</td>
<td>331 ± 12*</td>
<td>325 ± 1*</td>
</tr>
<tr>
<td>Wall thickness (μm)</td>
<td>35 ± 3</td>
<td>42 ± 3</td>
<td>42 ± 4</td>
</tr>
<tr>
<td>Wall-to-lumen ratio</td>
<td>0.12 ± 0.01</td>
<td>0.13 ± 0.01</td>
<td>0.13 ± 0.02</td>
</tr>
<tr>
<td>Myogenic tone (%)</td>
<td>2 ± 2</td>
<td>0.4 ± 0.4</td>
<td>2 ± 2</td>
</tr>
<tr>
<td>PE-induced tone (%)</td>
<td>35 ± 4</td>
<td>24 ± 3*</td>
<td>26 ± 4*</td>
</tr>
<tr>
<td><strong>Mesenteric arteries</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diameter (μm)</td>
<td>339 ± 6</td>
<td>343 ± 6</td>
<td>336 ± 12</td>
</tr>
<tr>
<td>Wall thickness (μm)</td>
<td>41 ± 2</td>
<td>43 ± 3</td>
<td>36 ± 2</td>
</tr>
<tr>
<td>Wall-to-lumen ratio</td>
<td>0.12 ± 0.01</td>
<td>0.13 ± 0.01</td>
<td>0.11 ± 0.01</td>
</tr>
<tr>
<td>Myogenic tone (%)</td>
<td>0.2 ± 0.2</td>
<td>0.5 ± 0.3</td>
<td>24 ± 1*</td>
</tr>
<tr>
<td>PE-induced tone (%)</td>
<td>4 ± 2</td>
<td>5 ± 4</td>
<td>46 ± 3**</td>
</tr>
</tbody>
</table>

* P < 0.05 versus CON.
† P < 0.05 versus CON-LIS.
² P < 0.05 versus CON-LIS.
³ P < 0.05 versus LS-LIS.
⁴ P < 0.05 versus CON-LIS.
⁵ P < 0.05 versus LS-LIS.
3A), suggesting significant activity of contractile prosta-
glandins in the latter. In the mesenteric arteries, a similar re-
duction in ACh-induced dilatation during LS-LIS was observed,
albeit to a lesser extent (Fig. 2B). Incubation with indometh-
acin significantly further reduced the response in the LS-LIS
group while leaving ACh-induced dilation in CON and CON-
LIS unaffected (Fig. 3B). These findings suggest a more
prominent role for dilatory prostaglandins in mesenteric
compared with renal arteries during LS-LIS.

Discussion

In accord with our hypothesis, we found that dietary so-
dium restriction, along with an increased blood pressure
response, modifies the vascular effects of maintenance treat-
ment with ACEi in resistance vessels. These effects were not
uniform across the vascular bed. Baseline vessel character-
istics were modified by ACEi in renal vessels, without a
further change during the combination with low sodium,
whereas in mesenteric vessels, ACEi as such had no effect,
but the combination with low sodium led to increased myo-
genic tone and \( \alpha \)-adrenergic responsiveness. Endothelial
function was modified by the combination ACEi with low
sodium compared with ACEi in both vascular beds, with
reduced endothelium-dependent vasodilation. In mesenteric
vessels, this was associated with an increased role of vasodi-
lator prostaglandins, whereas in renal vessels this was asso-
ciated with an increase in vasoconstrictor prostaglandins.

Whether these effects are cause or consequence of the en-
hanced response to ACEi cannot be derived from our data.

In mesenteric arteries, lisinopril per se did not have an
effect on baseline vascular parameters. However, additional
sodium restriction enhanced the propensity to increased va-
soconstriction, a situation more likely to be a counter action
than the cause of an enhanced blood pressure reduction.

The lisinopril per se induced changes in renal arteries are
in line with increased renal blood flow found in experimental
(Numabe et al., 1994) and human studies (Navis et al., 1987;
Heeg et al., 1989). Also, vascular remodeling with increased
vessel dimensions in response to long-term increase in flow
after ACE inhibitor therapy seems in line with previous
studies (Gibbons and Dzau, 1994; Reddi and Bollineni, 2001).
However, it should be noted that the in vivo effects of ACE
inhibition on renal hemodynamics also involve effects on
postglomerular vessels (Heeg et al., 1989), leading to an
altered balance of pre- and postglomerular resistance. The
resulting reduction in glomerular pressure probably contrib-
utes to the long-term renoprotective effects of ACE inhibi-
tion, in addition to the effects of lower systemic blood pres-
sure (Heeg et al., 1989; Sanchez et al., 1991). In the present
study, the effect of lisinopril on preglomerular renal arteries
was not modified by dietary sodium restriction, implying that
an enhanced response to ACE inhibition is not due to change
in baseline vascular morphology or function but probably due
to the enhanced blood pressure reduction. Thus, whereas

Fig. 2. Endothelium-dependent and -independent dilation in renal and mesenteric arteries. Full concentration-re-
sponse curves to and ACh and SNP in renal arteries (A, top) and small mesenteric arteries (B) from healthy control
rats (CON), rats chronically treated with lisinopril on a control diet (CON-LIS, 2% NaCl), or a low sodium diet
(LS-LIS, 0.05% NaCl). Data are mean ± S.E.M. of \( n = 8 \) to 10 observations in ACh-induced dilation and \( n = 4 \) to 5 in
SNP-induced dilation. *, \( P < 0.001 \) for CON-LIS versus
CON (repeated measures ANOVA). †, \( P < 0.05 \) for CON-
LIS versus LS-LIS (repeated measures ANOVA).
mesenteric arteries are considered resistance vessels regulating blood pressure (Luscher et al., 1992) and become constricted during reduced blood pressure, the renal vessels ensure renal blood flow and remain dilated. Therefore, the effect of additional sodium on baseline vascular beds reveals the heterogeneity of their function rather than explaining enhanced therapy response.

Endothelium-dependent dilation during maintenance ACE inhibition per se did neither improve nor attenuate in the present study. This may seem at variance with many studies reporting endothelial function during ACE inhibition in cardiovascular disease (Atkinson, 1995; Hutri-Kahonen et al., 1997; Mancini, 2000; Nunes et al., 2000; Enseleit et al., 2001). However, less is known about the effect of maintenance treatment with ACE inhibitors on apparently normal endothelial function in healthy conditions. In aortic rings of normal Wistar rats kept on a regular sodium diet, maximal dilation to ACh was increased from 70% in untreated rats to 90% after 6-week ramipril treatment (Berkenboom et al., 1995). In the present study, however, we studied small mesenteric resistance arteries and renal arteries which already showed near 100% relaxation to ACh, i.e., unlike the aorta, there may not be much to be gained by ACE inhibition.

Atkinson et al. (1994) found improved maximal relaxation to ACh in mesenteric arteries of normal WAG/Rij rats after ACE inhibitor treatment. However, the untreated rats in their study developed a time-dependent decrease in maximal ACh induced dilation in mesenteric artery, suggesting an improvement of ACh induced relaxation due to prevention of age-induced endothelial dysfunction (Atkinson et al., 1994; Atkinson, 1995). In our 3-week treatment compared with the treatment of several months of Atkinson et al. (1994), reduction of age-induced dysfunction due to ACE inhibition could not be expected.

In combination with low sodium, ACE inhibitor therapy reduced ACh-induced relaxation both in small renal and mesenteric arteries. One other rat study also reported impairment of apparently normal endothelial function in renal arteries after chronic therapy (Barton et al., 2000). After treatment with the ETA receptor antagonist LU135252, the relaxation of renal arteries to ACh was reduced in salt-treated salt-resistant Dahl rats. Interestingly, COX-inhibition with indomethacin acutely normalized this impairment. Evidence from studies with spontaneously hypertensive rats using indomethacin and PGH2/TXA2 receptor blockers (e.g., SQ 29,548) indicate that endothelium-derived PGH2 and TXA2 are contractile factors in intrarenal arteries that may underlie impaired relaxation to ACh (Dai et al., 1992; Fu-Xiang et al., 1992). Numerous studies have addressed the role of prostaglandins during changes in dietary sodium (Hocherl et al., 2002), but the impact on small vessels is less well known. In the present study, indomethacin also partially restored ACh induced relaxation of renal arteries of lisinopril treated rats during low sodium. Thus, our findings support involvement of COX-derived vasoconstrictive PGs, such as PGH2 and TXA2, in development of decreased ACh-induced dilation in renal arteries during LS-LIS. The exact identity of the PG involved however, cannot be determined from these data because we did not test specific PG modulators.

Relaxation to ACh in mesenteric arteries of lisinopril-treated rats during LS was also decreased, but in contrast to renal arteries, this occurred despite an apparent enhanced contribution of dilative prostaglandins. Hence, the effect of ACEi under LS on endothelium-derived prostaglandins seems to be differentially altered in the two artery types, with an increase in constrictive prostaglandins in renal, and an increase in dilative prostaglandins in mesenteric arteries. One way to explain this apparent discrepancy may be a differential involvement of specific COX isoforms in both vascular beds. In recent years, two different COXs have been described (Smith et al., 1996). Of these, COX-1 is considered the constitutive isoform because it is predominantly expressed at constant levels. COX-2 is considered the inducible isoform because its expression can be rapidly induced in cells involved in inflammation, including vascular endothelial cells. Interestingly, PGs are produced by COX-2 in much larger amounts compared with COX-1, which led to the hypothesis of the existence of “good” versus “bad” PGs. In this concept, COX-1 generates good PGs for physiological “housekeeping functions”, including regulation of renal blood flow, whereas COX-2 forms the bad PGs involved in inflammatory reactions and responsible for inflammatory signs such as capillary edema and vasodilation (Parente and Perretti, 2003). However, the terms constitutive and inducible have
been noted to be too strict to denote regulation of COX-1 and -2, and both COX-1 and COX-2 are apparently involved in physiological as well as pathophysiological processes (Vane et al., 1998; Katori and Majima, 2000). This raises the possibility that in our study COX-1 and -2 expression and/or function in the renal versus mesenteric arterial bed was differentially affected after ACEi during LS, resulting in opposite production of PGs after endothelial stimulation with ACh. Interestingly, exposure of the mesenteric vascular bed to indomethacin, SC-560 (selective inhibitor of COX-1), or NS-398 (selective inhibitor of COX-2) was reported to reverse the hyporeactivity to noradrenaline and the increased vaso-dilatation to ACh in portal hypertensive rats, with NS-398 being more potent than the two other inhibitors (Potenza et al., 2002). Such findings indicate that endothelial COX-1 and -2 may also differentially affect vascular reactivity within one vessel type (i.e., mesenteric) under certain conditions. It would be of interest therefore, to study the effects of low sodium during ACE inhibition by using specific inhibitors of COX-1 and -2, in combination with inhibitors of downstream synthases and/or PG receptor antagonists.

The impact of our findings on the target organ protection in disease conditions also remains to be studied. The effect of adding sodium restriction to ACEi on intermediate parameters can be classified as favorable, with further reduction of blood pressure and proteinuria. As to the vascular effects observed here, it is doubtful whether these are favorable, or should, by contrast, be considered as an unwanted side effect that limits the eventual therapeutic benefit of the enhanced effects on the blood pressure (and/or proteinuria) on outcome in terms of target organ protection. A prior study from our group provides support for the latter assumption. In experimental nephritic syndrome (Wapstra et al., 1996), low sodium potentiated the responses to ACEi of blood pressure and proteinuria, as well as renal outcome in terms of end-organ damage (focal sclerosis). However, the improvement in end-organ damage was considerably less than would have been expected from the improvement in blood pressure and proteinuria. If our present data implicate that the enhanced efficacy of ACEi is accompanied by possibly unwanted vascular effects, this example illustrates that it would be unwise to discard low sodium as an adjunct to ACE inhibition, because still the overall outcome is better than with ACEi alone. Rather, our findings provide a rationale to design additional treatment strategies, to preserve the poten-tiated treatment effect while preventing possibly unfavorable vascular side effects. Considering the role of prostaglandins in the altered endothelial function, the combination with maintenance treatment with COX inhibition would be of interest. However, the heterogeneity of the involvement of prostaglandins across the vascular bed should be specifically consid-ered.

In conclusion, the combination of low sodium with ACE inhibition results in distinct vascular effects, along with an enhanced blood pressure response in healthy animals. It is uncertain from our data whether the vascular effects are cause or consequence from the enhanced blood pressure response. Endothelium-derived vasodilation was reduced, which raises the possibility that the vascular effects are unfavorable in terms of long-term organ protection. Further studies should explore the impact of these vascular changes on long-term outcome in disease models, and investigate the potential of these vascular changes as a target for additional intervention. This should not be taken to discard low sodium as an adjunct to ACE inhibition, but rather as a rationale for further studies addressing the mechanism of actions of our therapies.

References


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