Aldosterone infusion with high-NaCl diet increases blood pressure in obese but not lean Zucker rats

S. Riazi,1 Osman Khan,1 Xinquin Hu,1 and Carolyn A. Ecelbarger1,2

1Department of Medicine, Division of Endocrinology and Metabolism, and 2Center for the Study of Sex Differences in Health, Aging and Disease, Georgetown University, Washington, District of Columbia

Submitted 16 December 2005; accepted in final form 26 March 2006

Riazi, S., Osman Khan, Xinquin Hu, and Carolyn A. Ecelbarger. Aldosterone infusion with high-NaCl diet increases blood pressure in obese but not lean Zucker rats. Am J Physiol Renal Physiol 291: F597–F605, 2006.—Insulin-resistant, obese Zucker rats have blunted pressure natriuresis and are mildly hypertensive. This may involve inappropriate regulation of the renin-angiotensin-aldosterone system. To evaluate mechanisms underlying this defect, we employed the model of aldosterone escape. Male lean (L) and obese (O) Zucker rats were infused with aldosterone (2.8 μg/g body wt1/3) via osmotic minipump while being fed a 0.02% NaCl diet (LS). After 4 days, six rats of each type were switched to a high-NaCl (HS) diet (4%) for 4 additional days. Mean arterial blood pressure was measured by radiotelemetry was significantly increased by the HS diet only in obese rats (final mean mmHg): 104 (LLS), 99 (LHS), 103 (OLS), and 115 (OHS). Obese rats had relatively increased renal cortical abundance of the bumetanide-sensitive Na-K-2Cl cotransporter (NKCC2) and whole kidney α- and β-ENaC (epithelial sodium channel) relative to lean rats. However, band density for the thiazide-sensitive (Na-CI cotransporter (NCC) was similarly reduced by HS in lean and obese rats (≈50%). Obese rats had relatively reduced creatinine clearances and plasma renin activities, effects exacerbated by HS. Furthermore, HS resulted in a 129% increase in urinary nitrates plus nitrites excretion in lean rats and led to, in contrast, a 46% reduction in obese rats. Plasma sodium and potassium concentrations were increased by HS in obese but not lean rats. Thus we demonstrate an impaired response to aldosterone infusion in obese relative to lean Zucker rats. This impairment may involve increased sodium reabsorption via NKCC2 or ENaC, decreased glomerular filtration rate, and/or nitric oxide bioavailability.

kidney; epithelial sodium channel; natriuresis; diuresis; NaPi-2; sodium hydrogen exchanger type 3; Na-K-2Cl cotransporter; BSC1; TSC; NCC; aquaporin; Na-CI cotransporter; hyperglycemia; proteomics

THE MECHANISMS UNDERLYING the relationship between obesity and hypertension are likely complex. Peripheral insulin resistance, which often accompanies obesity, may play a role in this relationship. Insulin resistance in humans and animal models has been associated with increased activity of the renin-angiotensin-aldosterone system (RAAS) (10, 12, 19, 24). Specifically, in the obese Zucker rat, a model characterized by morbid obesity coupled to severe insulin resistance and mild hypertension, increased renal cortical ANG II AT1 receptor mRNA and protein (35), AT1 binding activity (4), and losartan-mediated blood pressure decrease (1) have been demonstrated. Increased activity of ANG II would predict increased aldosterone activity in these animals, although this has not been adequately examined.

Aldosterone, a mineralocorticoid, is the key regulatory hormone in day-to-day sodium balance. In the kidney, aldosterone acts primarily on the distal tubule, i.e., distal convoluted tubule, connecting tubule, and collecting duct system, to increase sodium reabsorption (11). However, aldosterone may also increase sodium reabsorption in renal proximal brush border by increasing the abundance of the sodium/hydrogen exchanger (NHE3) (23). Most genomic actions of aldosterone are mediated through the mineralocorticoid receptor (MR), which has highest expression in the distal tubule (7). In addition, the distal tubule cells express 11-β-hydroxysteroid dehydrogenase-2 (11-β-HSD-2) (7) which protects the MR from glucocorticoids, which can also bind the MR but circulate in >100-fold greater concentrations than aldosterone. 11-β-HSD-2 converts glucocorticoids such as corticosterone into MR-inactive metabolites. How aldosterone action is mediated in the proximal tubule is not as clear. Nevertheless, inappropriately high aldosterone activity has been associated with a variety of cardiovascular diseases such as essential hypertension, congestive heart failure, and myocardial infarction (11). Therapy to antagonize aldosterone such as spironolactone or eplerenone treatment has been shown to successfully control and attenuate cardiovascular disease, primary aldosteronism, and associated end-organ damage (8, 16, 28).

Nevertheless, when plasma aldosterone levels are inappropriately high, relative to NaCl intake, NaCl reabsorption and retention do not continue at the same level, indefinitely. Humans and animals undergo a physiological adaptive process known as “aldosterone escape” in which a natriuresis occurs and distal tubular NaCl reabsorption is attenuated despite high or even clamped aldosterone levels (3, 30). This process has been characterized at the renal level in young, healthy, male rats and involves downregulation of the renal protein abundances of one major sodium transporter, i.e., the thiazide-sensitive Na-CI cotransporter (NCC) of the distal convoluted tubule (34). In addition, the lower band (70 kDa) of the γ-subunit of the epithelial sodium channel (ENaC) was downregulated (34). This band region has been shown to be increased by low-NaCl diets or by aldosterone infusion (27). However, α-ENaC, a protein also strongly upregulated in abundance by aldosterone, was not changed in escape. Thus aldosterone escape involves downregulation of some but not all aldosterone-regulated proteins of the distal tubule. Nevertheless, the role of changes in proximal and thick ascending limb...

http://www.ajprenal.org 0363-6127/06 $8.00 Copyright © 2006 the American Physiological Society F597
(TAL) sodium reabsorption is not clear. Kohan and Knox (22) showed an increase in fractional delivery of sodium to cortical collecting tubules of deep and superficial nephrons, in rats infused with DOCA, an aldosterone analog, and given isotonic saline, suggesting possible involvement of the late proximal tubule, TAL, along with the distal convoluted tubule in enhancing the natriuretic process. Knepper and colleagues (33) showed a nitric oxide (NO)-dependent increase in NHE3 abundance in aldosterone escape which was abolished by superimposed infusion of a NO synthase inhibitor, Nω-nitro-l-arginine methyl ester (l-NAME). They also reported that l-NAME administration uncovered an escape-associated reduction in renal bumetanide-sensitive Na-K-2Cl cotransporter (NKCC2) abundance. Because obese Zucker rats may have increased activity of the RAAS, and increased renal NCC abundance (6, 20), we hypothesized that they might also have a decreased ability to escape from aldosterone via the same downregulation. Therefore, here we compare aldosterone escape in young, male, obese Zucker rats with their lean age mates. Blood pressure, via radiotelemetry, and urinary sodium and potassium excretion are measured over the course of the escape. The abundances of major renal sodium transporters, exchangers, and channels, as well as endothelial NO synthase (eNOS or NOSIII) are measured in the kidney by semiquantitative immunoblotting.

MATERIALS AND METHODS

Animals, study design, and blood pressure monitoring. Twenty-four male Zucker rats [12 lean (FA/) and 12 obese (fa/)] were obtained from Charles River Laboratories (Wilmington, MA) at 9 wk of age. The animal protocol is illustrated in Fig. 1. After a brief (3 day) equilibration period, under isoflurane anesthesia (Isoflo, Abbot Laboratories, North Chicago, IL), a subset (n = 10/body type) was implanted with radiotelemetric transmitters (Data Sciences International, St. Paul, MN) to measure blood pressure (32). Computer data-acquisition software was configured to take a 10-s blood pressure measurement every 10 min over the course of the study. During this study to facilitate daily collection of urine and measurement of feed and water intake. Urine was collected daily with addition of 30 μl of an antibiotic cocktail containing (8.2 mg/ml penicillin G, 261 mg/ml streptomycin, and 0.5 mg/ml amphotericin, Sigma) on day 5 to better preserve urine for analysis of nitrates plus nitrates (NOx). All protocols were approved by the Georgetown Animal Care and Use Committee, an Association for Assessment and Accreditation of Laboratory Animal Care International (AAALAC)-approved facility.

Sample preparation. Rats were euthanized by decapitation and trunk blood was collected into both heparinized- and K2-EDTA tubes (Vacutainer, Becton-Dickinson, Franklin Lakes, NJ). Whole blood was centrifuged at 1,500 g (Sorvall RT 6000 D, Sorvall, Newtown, CT) at 4°C for 20 min to separate plasma. Both kidneys were rapidly removed. The left kidney was homogenized whole, and the right kidney was dissected into cortex, inner stripe of outer medulla, and inner medulla and each region was individually prepared for blotting as previously described (14, 15).

Plasma and urine analyses. Plasma aldosterone and renin activity were measured by radioimmunoassays (Coat-a-Count, Diagnostic Products, Los Angeles, CA and Gamagelco Plasma Renin Activity RIA kit, DiaSorin, Stillwater, MN, respectively). Plasma and urine NOx was measured by colorimetric assay (Nitrate/Nitrite Colorimetric Assay Kit, Cayman Chemical, Ann Arbor, MI). Urinary sodium and potassium were measured by an ion-selective electrode system (EL-ISE Electrolyte System, Beckman Instruments, Brea, CA) and osmolality by freezing-point depression (The Advanced Osmometer, model 3900, Advanced Instruments, Norwood, MA).

Immunoblotting. Initially, Coomassie-stained “loading gels” were done on all sample sets to assess the quality of the protein by sharpness of the bands and to confirm equality of loading, as previously described (13, 15). For immunoblotting, 2–30 μg of protein from each sample were loaded into individual lanes of minigels of 7, 10, or 12% polyacrylamide (precast, Bio-Rad, Hercules, CA). We used our own polyclonal antibodies against NCC, −, −, −, and 1-subunit of Na-K-ATPase was obtained from Upstate Biotechnology (Lake Placid, NY).

Statistics. Data were analyzed by two-way ANOVA (body type × treatment) to determine overall effects of body type or treatment. Also, to determine differences between specific mean pairs, data were also analyzed by one-way ANOVA followed by Tukey’s multiple comparisons test or Kruskal-Wallis ANOVA on ranks followed by Dunn’s multiple comparisons test (when data were not normally distributed or variance was different between groups). Multiple comparison tests were only applied when a significant difference was determined in the ANOVA analysis, P < 0.05.

RESULTS

Blood pressure. Mean arterial blood pressure (MAP) is plotted in Fig. 2A. There was a small but significant difference in MAP between lean and obese rats at the outset of the study,
Significant difference from the other 3 groups by 1-way ANOVA followed by the study: appeared. In Fig. 2, we show the change in MAP from infusion), MAP differences between lean and obese rats disswitched to a LS diet (and began receiving aldosterone by aldosterone escape.

Fig. 2. Mean arterial blood pressure (MAP) in lean and obese rats during (a) high-NaCl diet. This difference was eliminated during the period of low-NaCl diet and aldosterone infusion. Obese rats, but not lean, had an increase in blood pressure on high-NaCl diet. B: delta MAP from baseline (average of day −4 and −3) for the low-NaCl (LS) period of the study (5 days, days 0 to +4) and for the next 4 days (HS or LS, days +5 to +8). There was a significant fall in blood pressure in the obese rats in the first period, when all rats received low-NaCl diet and were infused with aldosterone. In the second period, only obese rats responded to the high-salt diet with an increase in blood pressure. *Significant (P < 0.05) difference between lean and obese rats by 2-way ANOVA. †Significant difference from the other 3 groups by 1-way ANOVA followed by Tukey’s multiple comparisons test.

as we previously showed (5, 6, 21). However, after rats were switched to a LS diet (and began receiving aldosterone by infusion), MAP differences between lean and obese rats disappeared. In Fig. 2B, we show the change in MAP from baseline in the four groups of rats for the two main periods of the study: 1) LS for all rats (days 0 to +4) and 2) HS for six rats and continued LS for the remaining six (days +5 to +8). Delta MAPs were determined by subtracting mean baseline MAPs from mean “period” MAPs. Mean baseline MAP was calculated for each rat as the average of MAP measurements taken over the 48-h period (days −4 to −3) when all rats were in the basal state receiving a normal chow diet containing 1% NaCl. Mean period MAPs were likewise determined for each rat by averaging all blood pressure measurements for period 1 (a 5-day period, 720 total measurements/rat) and the subsequent 4-day period 2 (576 measurements/rat). These numbers were then averaged for the group mean and statistically compared by one- and two-way ANOVA. In the first period (days 0 to +4), when all obese and lean rats received LS diet, obese rats had a significant fall in blood pressure, not observed in the lean, suggesting that the obese rats were more salt sensitive, with regard to blood pressure, than were the lean. In the next period (days +5 to +8), when half of rats in each body type were switched to HS, the obese rats responded with an increase in blood pressure, whereas the lean rats were relatively unresponsive. The obese rats receiving LS maintained their lowered blood pressure.

Sodium/potassium excretion. Urinary sodium excretion increased markedly after only 1 day of the HS diet in both lean and obese rats (Fig. 3A). Obese rats excreted more sodium, likely a reflection of greater dietary intake. When urine sodium was normalized to dietary intake (Fig. 3B), in general there were no differences between lean and obese except for the final day, where there was a slight but significant increase in the obese relative to lean. Similarly, absolute urinary potassium excretion was, in general, higher in the obese rats (Fig. 3C). All rats underwent a relative kaliuresis between “day 0” and “day 1” likely due to the aldosterone infusion. This kaliuresis (relative to prealdosterone infusion day 0) was transient in the lean rats but seemed to persist in the obese rats. A second kaliuresis occurred after initiation of the HS diet (day 5). This was relatively blunted in the obese rats. When urinary potassium was normalized to dietary intake (Fig. 3D), the stark, spiked, kaliuresis in the lean rats both after initiation of the aldosterone infusion or the high-NaCl is even more apparent. As a result of this, lean rats had a significantly lower Na⁺-to-K⁺ ratio, in their urine on day 1 (Fig. 3E), the first day after the beginning of aldosterone infusion; i.e., the ratio in lean rats was 0.015 ± 0.001 and in obese rats it was 0.019 ± 0.005 (n = 12), P = 0.026 (this is difficult to appreciate from the figure due to the scale). In contrast, on day 6 (2 days after initiation of the HS period) lean HS rats had a significantly higher Na⁺-to-K⁺ ratio relative to obese HS rats. Urinary volume was higher in the obese rats over the course of the experiment and was increased in both lean and obese rats by HS (Fig. 3F).

Physiological parameters. Dietary treatment did not affect final body weight (Table 1). Similarly, plasma sodium and potassium levels were not affected by diet in the lean rats; however, for obese rats, the obese HS rats were relatively hyperkalemic and hypynatremic. In contrast, the obese LS rats were relatively hypokalemic, although not significantly different from the lean rats. Plasma aldosterone levels were not significantly different among groups, as expected due to the high rate of infusion in all groups. They were an order of magnitude higher than normal physiological levels on moderate NaCl intake (6, 20). Plasma renin activity was reduced by both HS and in obese rats by two-way ANOVA, so that mean plasma renin activity in obese HS rats was only 2.3% of lean LS rats. Creatinine clearance (CCl), expressed on a per body weight basis, was significantly reduced in obese rats with a slight exacerbation of this reduction with HS. Furthermore, when not corrected for body weight, CCl was still significantly reduced in obese rats (ml/min): 1.5 ± 0.1, 1.1 ± 0.2, 0.8 ± 0.2, and 0.7 ± 0.2 in lean LS, lean HS, obese LS, and obese HS groups, respectively, P = 0.009. This was partly due to significantly decreased urine creatinine, which was 28% lower in obese rats than lean, on the final day of the study, irrespec-
Plasma creatinine was variable within the treatment groups, so there were no significant differences by one- or two-way ANOVA. Mean plasma creatinine concentrations were (μmol/l) 18 ± 2, 31 ± 4, 35 ± 11, and 58 ± 23 in lean LS, lean HS, obese LS, and obese HS groups, respectively (P = 0.11). In addition, plasma NOx did not differ significantly among groups. However, urine NOx excretion was increased in obese rats relative to lean, but HS caused a 129% increase in excretion in lean rats, but resulted in a 46% decrease in the obese rats. Final urine osmolality was not different among groups. Remarkably, fractional excretion of sodium (clearance of sodium relative to creatinine) was significantly increased in the obese HS rats (P < 0.04), relative to the lean.

Proximal tubule sodium transporters. In Fig. 4, left, we show immunoblots of cortex homogenates (which are enriched...
in proximal tubules) probed with antibodies against NHE3, the NaPi-2, and the α1-subunit of Na-K-ATPase. In Fig. 4, right, are bar graph summaries of the densitometry. (Na-K-ATPase is also expressed in the TAL and in the distal tubule also found in the cortex of the kidney, but these segments of the kidney make up a much lower proportion of the cells in a cortex homogenate; thus the signal for Na-K-ATPase can be mainly attributed to the proximal tubule.) There was no significant difference in protein abundance for NHE3 or the α1-subunit of Na-K-ATPase; however, NaPi-2 (84-kDa band) was markedly reduced in the obese rats relative to lean, by two-way ANOVA (body type). In the cortex, however, NKC2 abundance was significantly reduced in the lean but not the obese HS rats (by two-way ANOVA). NHE3 abundance was not significantly different among any of the groups. However, α1 Na-K-ATPase was significantly reduced in the lean LS group relative to the other three groups in outer medulla and increased in both HS and in obese rats (by two-way ANOVA).

**Distal tubule and collecting duct.** Distal sodium transporters and channel subunits were examined in whole kidney homogenates. The abundance of NCC was significantly reduced in both lean and obese rats by HS (Fig. 6), with no significant differences between body types. The α- and β-subunits of ENaC were increased in obese rats and not affected by diet. The major band of γ-ENaC (85-kDa) was reduced in the lean LS rats relative to the obese LS. Finally, HS decreased the abundance of the 70-kDa band of γ-ENaC in both lean and obese rats.

**eNOS.** We examined eNOS abundance in cortex, outer medullary, and inner medullary homogenates (Fig. 7). Abundance of eNOS was significantly increased in obese LS compared with lean LS in cortex by one-way ANOVA (P = 0.003). There was a marked increase in eNOS abundance in response to body type. In the cortex, however, NKC2 abundance was significantly reduced in the lean but not the obese HS rats (by one-way ANOVA). NHE3 abundance was not significantly different among any of the groups. However, α1 Na-K-ATPase was significantly reduced in the lean LS group relative to the other three groups in outer medulla and increased in both HS and in obese rats (by two-way ANOVA).

### Table 1. Physiological data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lean LS</th>
<th>Lean HS</th>
<th>Obese LS</th>
<th>Obese HS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final body weight, g</td>
<td>260±9B</td>
<td>275±5B</td>
<td>374±8A</td>
<td>355±15A</td>
</tr>
<tr>
<td>Plasma sodium, mmol/l</td>
<td>143±2B</td>
<td>140±1B</td>
<td>144±2B</td>
<td>152±2A</td>
</tr>
<tr>
<td>Plasma potassium, mmol/l</td>
<td>5.5±0.3AB</td>
<td>5.5±0.3AB</td>
<td>4.6±0.3B</td>
<td>6.6±0.6A</td>
</tr>
<tr>
<td>Plasma aldosterone, mmol/l</td>
<td>14±0.9</td>
<td>16±2</td>
<td>18±3</td>
<td>21±3</td>
</tr>
<tr>
<td>Plasma NOx, μmol/l</td>
<td>6.1±0.6</td>
<td>8.2±1.3</td>
<td>7.2±2</td>
<td>11±2.6</td>
</tr>
<tr>
<td>Creatinine clearance, ml/min/1-kg body wt⁻¹</td>
<td>5.8±0.3A</td>
<td>4.1±0.9AB</td>
<td>2.3±0.5B</td>
<td>2.0±0.5B</td>
</tr>
<tr>
<td>Urine NOx (day 5), μmol/kg/1-day⁻¹</td>
<td>0.96±0.3A</td>
<td>2.20±0.3AB</td>
<td>6.01±1.5A</td>
<td>3.24±0.6AB</td>
</tr>
<tr>
<td>Urine osmolality, mOsm/kgH₂O</td>
<td>690±54</td>
<td>671±55</td>
<td>711±40</td>
<td>883±140</td>
</tr>
<tr>
<td>Fractional excretion of Na⁺ (day 8), %</td>
<td>0.08±0.04C</td>
<td>2.07±0.55AB</td>
<td>0.15±0.03BC</td>
<td>15.4±6.2A</td>
</tr>
</tbody>
</table>

Values are means ± SE, n = 6/group. NOx, nitrates plus nitrates. A,B,C Letters are assigned based on the outcome of Tukey’s multiple comparison’s test following a significant (P < 0.05) one-way ANOVA. The letter “A” is assigned to the highest mean in the row. Means with letters in common within a row are not significantly different from each other.

Fig. 4. Proximal tubule-associated sodium transporters. Immunoblots (left) and bar graph summaries of densitometry (right) are shown for sodium/hydrogen exchanger (NHE3), sodium-phosphate cotransporter (NaPi-2), and the α₁-subunit of Na-K-ATPase in cortex homogenates. Within each blot, all lanes are loaded with equal amounts of total protein. Each lane contains a sample from a different rat. Preliminary coomassie-stained gels confirmed equality of loading. *Significant (P < 0.05) difference between lean and obese rats by 2-way ANOVA. No differences were found for NHE3 or α₁ Na-K-ATPase.
to HS in both lean and obese rats in outer medulla by two-way ANOVA ($P < 0.01$). However, no differences were found due to body type. In the inner medulla, eNOS abundance was not significantly different between groups.

**DISCUSSION**

Pressure natriuresis is likely invoked during natriuretic and blood pressure escape from aldosterone infusion with HS.
feeding. In this report, we demonstrate that the obese Zucker rat indeed has a lesser capacity to maintain homeostatic control of blood pressure and plasma electrolyte concentrations with aldosterone infusion than does the lean Zucker rat. Under aldosterone clamp, the obese rats showed a greater sensitivity of blood pressure to dietary NaCl. This increase in blood pressure corresponded to a reduced suppression of the NKCC2 of blood pressure during aldosterone escape. However, a sub-sequent study by this group (33) revealed that when L-NAME, a NOS inhibitor, was superimposed on the aldosterone escape in cortex and pressure corresponded to a reduced suppression of the NKCC2 of blood pressure in lean versus obese LS rats. This increase in blood pressure, in these rats, relative to lean. However, in obese rats, a significant decrease was only observed in outer medulla, whereas in the lean rats, this reduction in abundance extended into the cortical homogenates, presumably cortical TAL. Thus, it is possible that this difference in the downregulation of NKCC2 contributed to relative NaCl retention in the obese rats. Inappropriately high renal expression of NKCC2 has been reported in at least two hypertensive rat strains (2, 9).

The reduction in NKCC2 during aldosterone escape disagreed somewhat with the study of Wang et al. (34) in which NKCC2 abundance was not changed in young, male Sprague-Dawley rats undergoing aldosterone escape. However, a subsequent study by this group (33) revealed that when L-NAME, a NOS inhibitor, was superimposed on the aldosterone escape protocol, NKCC2 abundance was decreased.

In addition, α- and β-ENaC abundances were increased in the obese rats, relative to lean, regardless of the level of dietary NaCl. Previously, we (6) found no significant differences in α-ENaC abundance between lean and obese rats, when aldosterone levels were not clamped, although we found increased β-ENaC abundance. α-ENaC abundance is strongly upregulated by aldosterone (27), as is the activity of the ENaC multimeric channel (29). This may suggest a greater sensitivity to the same circulating level of aldosterone in the obese rats, relative to lean with regard to α-ENaC expression. Thus increased ENaC activity in conjunction with the HS would be expected to result in greater sodium retention and increased blood pressure, in these rats, relative to lean. However, in agreement with findings of Wang et al. (34) in the Sprague-Dawley rats, the abundance of this subunit did not seem to be highly regulated by the level of NaCl in either the lean or obese rats, suggesting that the downregulation of this protein is not normally a mechanism via which escape is mediated.

However, marked downregulation of the NCC has been associated with aldosterone escape (34). Moreover, previously we (6, 20) showed an increase in NCC abundance in young, male obese Zucker rats relative to lean age mates. Nonetheless, we did not detect any difference in the downregulation of renal NCC abundance between lean and obese rats treated with HS. Band density for the major band of NCC (165 kDa) was decreased to between 45 and 55% of body type LS controls in both lean and obese rats (Fig. 6). This suggests that differential regulation of this protein, at least its abundance, did not play a role in reduced “escape” capability in the obese rats.

However, decreased glomerular filtration rates (GFR), as assessed by reduced CCl, may have contributed to impaired escape in the obese rats. CCl was reduced in obese rats, relative to lean, irrespective of level of dietary NaCl (Table 1). In fact, obese LS rats had 50% lower CCl than did lean LS rats, suggesting that the infusion of aldosterone alone resulted in a fall in GFR. Furthermore, HS on top of the clamp led to a further reduction in CCI in both lean and obese rats of ~15–30%. Previously, we (6) and others (1) observed no differences or even increased GFR or CCl in obese relative to lean Zucker rats, when aldosterone levels weren’t clamped and rats were fed more normal levels of NaCl. Thus we suggest that this relatively decreased GFR may have increased salt sensitivity of the obese rats with regard to the ability to normalize blood pressure.

The effect of this fall in GFR on sodium excretion may have been partly ameliorated by activation of glomerular tubular balance. Because sodium entry into the proximal tubule would be less, sodium reabsorption would be proportionally reduced. This might occur from or result in decreased abundance of proximal tubule sodium transporters. We observed a marked decrease in NaPi-2 protein, a sodium-coupled phosphate co-

Fig. 7. Endothelial nitric oxide synthase. Immunoblot (left) and bar graph summaries of densitometry (right) are shown for eNOS in cortex (CTXH), outer medulla (OMH), and inner medulla (IMH) homogenates. Within each blot, all lanes are loaded with equal amounts of total protein. Each lane contains a sample of total protein from cortex and eNOS Western blot membranes. Two different samples were used. Comparisons were within each blot and each OFH. The effect of L-NAME on eNOS expression is shown for eNOS in cortex (CTXH), outer medulla (OMH), and inner medulla (IMH) homogenates. Each lane contains a sample of total protein from cortex and eNOS Western blot membranes. Two different samples were used. Comparisons were within each blot and each OFH.
transporter of the proximal tubule in the obese rats relative to lean. This, similar to CCl, was reduced independently of dietary NaCl level. We previously observed reduced NaPi-2 abundance in the cortex of older (6-mo-old) diabetic, obese Zucker rats that, similarly, had reduced CCl, relative to lean age mates. However, it is also possible that the fall in GFR and the fall in NaPi-2 protein are not causally related. There was no similar reduction in NHE3 or in the α1-subunit of Na-K-ATPase in the cortex.

Both plasma sodium and potassium levels were elevated in the obese rats on HS, whereas HS had no bearing on plasma Na+ and K+ in the lean rats. The hypernatremia in obese rats we suggest may have resulted from inappropriate sodium retention, although we could not clearly show, using classic balance techniques, a defect in the natriuresis in the obese rats. However, there may have been some blunting in the speed of onset of the natriuretic response in the obese rats in that on day 5, the second day after initiation of the HS diet, the lean rats had peaked at the level of 440 ± 40 μmol Na+/g diet, whereas urine Na+ was still climbing in the obese rats (309 ± 51; P = 0.07), between these two groups by unpaired t-test. Decreased GFR could result in potassium as well as sodium retention. Collecting duct flow rate is a major determinant of potassium secretion (26), and in support of this we found a relative blunted kaliuresis in the obese rats, when offered the HS diet.

Despite lowered GFR in the obese rats, renin activity was suppressed, relative to lean. This confirms our (20) and previous findings of Alonso-Galicia et al. (1) of relatively reduced renin activity in nonaldosterone clamped obese vs. lean Zucker rats. In fact, this pattern was exacerbated in the obese rats on the HS diet. That is, renin activity was reduced in the lean rats undergoing escape from 69 ± 14 to 20 ± 11 ng·ml⁻¹·h⁻¹, a drop of 70%. However, in the obese rats it was reduced from 25 ± 5 to 1.6 ± 0.6, a drop of 93%. This suggests higher, rather than lower, macula densa NaCl load in the obese relative to lean rats. This possibly could explain the reduction in GFR in these rats as the tubuloglomerular feedback response to high macula densa NaCl load would result in the release of vasoconstrictors acting on the afferent arteriole (25).

Finally, there may be a role for impaired NO bioavailability in determining the relative inability of the obese rats, relative to lean, to escape with regard to blood pressure. Fijiwara et al. (17) demonstrated impaired renal NOx production in response to elevated renal perfusion pressure in obese Zucker rats. In fact, we found that urine NOx, even when normalized by body weight, was 626% higher in the obese rats relative to lean LS rats. The addition of high NaCl in the diet resulted in a twofold increase in urinary NOx in the lean, but actually an ~46% drop in the obese. Thus the obese rats were unable to respond to the HS diet with an increase in NO, perhaps because the system was already maximally stimulated in response to the aldosterone infusion alone. Furthermore, urine NOx correlated with cortex eNOS protein in that it was clearly lowest in the lean LS rats and highest in the obese LS rats. This inability to produce additional NO to respond to the high-NaCl challenge may have reduced proximal tubule sodium reabsorption in these rats, shifting more sodium to the TAL and distal tubule, which may have reduced GFR, further confounding the situation.

Therefore, in summary, we demonstrate an impaired response to aldosterone infusion with regard to blood pressure and the normalization of serum sodium and potassium levels in obese relative to lean Zucker rats. This impairment may involve increased sodium reabsorption via NKCC2 or ENaC in the cortex, which were increased in the obese rats on HS relative to lean. In addition, decreased GFR and NO bioavailability may have a role in sodium retention.

ACKNOWLEDGMENTS

We thank Dr. J. Klein (Emory University) for use of the NKCC2 antibody.

GRANTS

This work was primarily supported by National Institutes of Health (NIH) Grant HL-073193 awarded to Georgetown University (PI, C. Ecelbarger), with additional salary support for S. Riazi, X. Hu, and C. Ecelbarger, which came from NIH Grants HL-074142 and DK-064872 (also to Georgetown University, with PI, C. Ecelbarger).

REFERENCES