Protein intake regulates the vasodilatory function of the kidney and NMDA receptor expression

Larry A. Slomowitz, Francis B. Gabbai, Ser J. Khang, Joseph Satriano, Sonia Thareau, Aihua Deng, Scott C. Thomson, Roland C. Blantz, and Karen A. Munger

Division of Nephrology and Hypertension, Department of Medicine, University of California San Diego and Veterans Administration San Diego Healthcare System, San Diego, California 92161

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First published July 8, 2004; doi:10.1152/ajpregu.00169.2003.—Glycine infusion profoundly increases renal blood flow by mechanisms that are not completely understood. Absence of a vasodilatory response in various experimental conditions [nitric oxide (NO) blockade in normal rats, experimental models of hypertension, diabetes mellitus, chronic glomerulonephritis, cyclosporine administration] is characterized by a significant decrease in proximal tubular reabsorption during amino acid infusion (5, 6, 8, 9). We and others have been interested in the mechanism by which protein feeding and amino acid infusion increase glomerular filtration rate (GFR) and renal blood flow (1, 5, 14, 15). We showed that angiotensin and NO are involved in the response, but these factors do not entirely explain the phenomenon. We know that diabetes, which is a state of high-protein intake for the rat, abolishes the glycine-induced renal vasodilation. Periodic eating of protein is known to result in increases in GFR, and it has been postulated that constant eating of high protein is associated with glomerular hyperfiltration (18). We also showed that whether the amino acid is a branched chain or nonbranched chain, amino acid affects the renal hemodynamic response (17). Therefore, type of proteins, the extent of hypertrophy and underlying disease state, and the activity of the NO and angiotensin II systems all contribute to the overall effect on renal hemodynamics and the response to amino acid infusions.

The N-methyl-D-aspartate (NMDA) receptor is a diheteromeric receptor complex that functions as a membrane calcium channel. Research in this area has been primarily conducted in central nervous system tissue, in which NMDA activation results in calcium entry and the stimulation of neuronal NO synthase (nNOS) activity. Glutamate and glycine are the major agonists leading to activation and channel opening. Recently, we demonstrated the presence of renal NMDA receptors and observed significant functional effects of inhibition of the NMDA receptor in the kidney that are not related to central nervous effects (11). Inhibition of these receptors caused marked renal vasoconstriction and a reduction in renal blood flow. The renal blood flow/GFR response to one of the normal agonists, glycine, which normally increases renal blood flow as discussed above, was nearly abolished in rats pretreated with two different types of NMDA receptor antagonists (11).

The current studies were devised to determine whether a chronic low-protein diet (LPD) would modify the glycine response and whether the renal NMDA receptor would be regulated by this maneuver. We examined the effects of prolonged restriction of protein intake to determine 1) whether the kidney response to glycine was altered by dietary protein intake, 2) whether this response is modified by angiotensin-converting enzyme (ACE) inhibitors as previously demonstrated by us (5, 6), and 3) whether NMDA receptor expression was altered by this maneuver. Therefore, we took a two-pronged approach by examining the expression of NMDA receptors by Western blot analysis and tested and evaluated the functional response to glycine in animals on normal diet and LPD and animals on the latter diet treated with an ACE inhibitor.

Address for reprint requests and other correspondence: K. A. Munger, Division of Nephrology and Hypertension, UCSD & VASDHS, Mail code 111-H, 3350 La Jolla Village Drive, San Diego, CA 92161 (E-mail: kmunger@vapop.ucsd.edu).

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MATERIALS AND METHODS

Male Wistar rats (Harlan) weighing 250–350 g were used in this study. Rats were placed on a LPD (8% protein, Low Renal Load Diet, no. 960331, ICN Biomedicals, n = 8). This diet has added methionine (0.3%) to maintain the needed levels of this amino acid in rats. Control rats were fed the normal rat chow (21% protein, Harlan TecLad, n = 7). After 2 wk of diet, renal function was evaluated by clearance and micropuncture methods. A second group of rats on LPD received the ACE inhibitor captopril (75 mg/l; n = 6; Sigma, St. Louis, MO) in the drinking water for 5 days before micropuncture studies. Kidney tissues were harvested from separate groups of rats receiving the identical diets for measurement of NMDA receptor protein by Western blot.

Micropuncture Protocol

The rats were anesthetized with Inactin (10 mg/100 g body wt ip BYK; Konstanz, Germany) and surgically prepared as previously described in our laboratory (7, 16). Briefly, the rats underwent tracheostomy and cannulation of the left jugular vein, left femoral artery, and bladder. The left kidney was exposed via a flank incision and placed in a Lucite cup. The cup surrounding the kidney was packed with cotton and 2% agar and the surface was covered with oil, and periodic plasma samples were obtained for [3H]inulin activity in plasma, urine, and tubular fluid collections from the femoral artery for measurement of afferent (P SF) and efferent arterioles were measured with a glass micropipette and these were bracketed by two (P SF) and efferent arterioles were measured with a glass micropipette (P). NaCl-NaHCO3 solution. The femoral artery catheter was connected to a desktop computer loaded with the WinDaq software (DATAQ Instruments, Gould Division, Hato Rey, Puerto Rico) connected to a servo-nulling pressure measurement device (IPM, San Antonio, TX). Inulin-SF was monitored as described in previous studies (7). Protein concentration in whole, two-kidney, GFR, and single-nephron plasma flow (SNPF), efferent arteriolar resistance (AR), efferent arteriolar resistance (ER), oncolytic pressure (π), and the glomerular ultrafiltration coefficient (LpA) were calculated as previously described (7, 16).

Western Blot Protein Analysis

In all the studies, urine was collected in preweighed containers under oil, and periodic plasma samples were obtained for [3H]inulin activity in plasma, urine, and tubular fluid monitored on a model B4530 Tru/Carb Packard liquid scintillation counter (Packard Instrument, Downers Grove, IL). GFR, SNCFR, absolute (APR) and fractional (FR) proximal tubular reabsorption were determined as described in previous studies (7). Protein concentration in systemic and efferent arteriolar plasma samples was measured by a microadaptation of the Lowry method (21).

Calculations

Glomerular capillary hydrostatic pressure (P G ) was calculated as P G = SF + πA, where πA corresponds to the oncolytic pressure at the level of the afferent arteriole (systemic oncolytic pressure). Single-nephron plasma flow (SNPF), efferent arteriolar resistance (AR), efferent arteriolar resistance (ER), oncolytic pressure (π), and the glomerular ultrafiltration coefficient (LpA) were calculated as previously described (7, 16).

Statistics

Paired data in a single experiment were compared with the paired t-test. ANOVA followed by Bonferroni correction was performed to obtain statistical significance between groups of animals. The level of statistical significance was defined as P < 0.05. Not significant comparisons are indicated by “ns.” All results are expressed as means ± SD.

RESULTS

Two weeks of LPD did not affect total body weight (control rats 344 ± 17 g vs. LPD 327 ± 20 g; ns). However, rats fed the LPD had significantly smaller kidneys after 2 wk (1.31 ± 0.15 vs. 1.07 ± 0.19 g, control vs. LPD left kidney weight, P < 0.05).

Renal Micropuncture Results

Control rats. Glycine infusion did not affect MAP (112 ± 10 vs. 108 ± 7 mmHg, ns). Similar to our previous findings, glycine administration in control rats resulted in a significant increase in GFR (2.8 ± 0.9 to 3.3 ± 0.9 ml/min, 2-kidney values, P < 0.038) and SNGFR (27.6 ± 6.9 to 40.1 ± 11.7 ml/min, P < 0.05; Fig. 1 and Table 1) (4–7, 9, 10). Urinary flow rate increased (5 ± 4 to 28 ± 18 µl/min, P < 0.005). Single-nephron blood flow (SNBF) was also increased from 143 ± 38 to 181 ± 57 ml/min (P < 0.05). The increase in SNBF was due to a statistically significant decrease in AR (38.9 ± 16 to 23.4 ± 9.4 Gdyne·s·cm−5, P < 0.05) and a numerical decrease in ER (27.8 ± 9.9 to 22.8 ± 11.8 Gdyne·s·cm−5, ns). Glycine infusion did not modify the trans-
Fig. 1. Effect of glycine infusion on SNGFR and fractional (FR) proximal tubular reabsorption. SNGFR, single-nephron glomerular filtration rate; LPD, low-protein diet; CAP, captopril.

capillary hydrostatic pressure gradient (36.8 ± 1.5 to 37.1 ± 3.5 mmHg, ns) because a significant increase in P_G (48.0 ± 1.5 vs. 59.5 ± 2.8 mmHg, P < 0.05) was paralleled by a significant increase in tubular pressure (11 ± 0.8 vs. 22 ± 2.6 mmHg, P < 0.05). The LpA increased from 0.30 ± 0.009 to 0.042 ± 0.015 nl·s⁻¹·mmHg⁻¹, but this increase failed to achieve statistical significance (P = 0.066). (Note: these LpA values for control animals are on the low range of normal. This finding is probably incidental and related to this group of rats. No historical controls were used. See Refs. 12 and 23 for similar values.) Afferent (systemic) protein concentration and oncotic pressure were mildly but significantly reduced during glycine infusion (4.6 ± 0.5 vs. 4.4 ± 0.4 g/dl and 14.1 ± 2.1 vs. 13.2 ± 1.9 mmHg, respectively, P < 0.05). No differences were observed in efferent arteriolar protein concentration and therefore oncotic pressure (7.4 ± 0.6 vs. 7.5 ± 0.7 g/dl and 28.2 ± 3.5 vs. 28.9 ± 4.7 mmHg, respectively, ns) between baseline and glycine.

Figure 1 presents the results of measurements of proximal tubular reabsorption. APR was measured in a subset of nephrons during baseline and then during glycine infusion. Increases in SNGFR (26.9 ± 7.5 to 34.8 ± 7.9 nl/min, P < 0.009) during glycine infusion were coupled with increases in APR (8.8 ± 2.3 vs. 9.4 ± 3.3 nl/min, ns) such that FR remained constant (0.34 ± 0.06 vs. 0.28 ± 0.08 nl/min, ns). (Note: absolute values for SNGFR are slightly different in Fig. 1 compared with Table 1 because Fig. 1 represents only the means of nephrons used to measure APR. The relative changes are the same. Statistics and n are based on the same animals as Table 1.)

LPD

Administration of LPD did not significantly modify baseline hemodynamics when compared with control rats. Table 1 and Fig. 1 present the results obtained in rats receiving LPD. Again, glycine did not increase systemic arterial pressure (122 ± 9 to 121 ± 5 mmHg, ns). In contrast with the control diet group, glycine infusion in rats receiving LPD did not increase GFR (2.6 ± 0.5 to 2.2 ± 0.3 nl/min, P < 0.015) and did not modify SNGFR (30.9 ± 4.5 vs. 33.2 ± 5.6 nl/min, ns). SNBF (149 ± 24 vs. 136 ± 38 nl/min, ns), ΔP (35 ± 3 vs. 35 ± 3 mmHg, ns), or either one of the glomerular arteriolar resistances (AR or ER). Urinary flow rate increased (6 ± 2 to 37 ± 13 μl/min, P < 0.005), in a ratio identical to rats on control diet, even though GFR remained constant. Significant increases were observed in P_G (51 ± 5 to 63 ± 8 mmHg, P < 0.05) and tubular hydrostatic pressure (16 ± 5 vs. 28 ± 7 mmHg) similar to the changes found in the control group, and a mild but significant increase was also observed in LpA.

Table 1. Glomerular hemodynamic findings in control, LPD, and LPD + CAP rats

<table>
<thead>
<tr>
<th></th>
<th>SNGFR, nl/min</th>
<th>SNBF, nl/min</th>
<th>P_T, mmHg</th>
<th>P_G, mmHg</th>
<th>P_SG, mmHg</th>
<th>ΔP, mmHg</th>
<th>ΔP/G, dynes·cm⁻¹</th>
<th>ER × 10⁹ dynes·cm⁻¹</th>
<th>π_A, mmHg</th>
<th>π_E, mmHg</th>
<th>LpA, nl·s⁻¹·mmHg⁻¹</th>
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<tbody>
<tr>
<td>Normal diet</td>
<td></td>
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<tr>
<td>(n = 7)</td>
<td>27.6±6.9</td>
<td>143±38</td>
<td>11.0±0.8</td>
<td>48.0±1.5</td>
<td>34.0±2.6</td>
<td>36.8±1.5</td>
<td>38.9±16</td>
<td>27.8±9.9</td>
<td>14.1±2.1</td>
<td>28.2±3.5</td>
<td>0.030±0.009</td>
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<tr>
<td>+Glycine</td>
<td>40.1±11.7*</td>
<td>181±57*</td>
<td>22.0±2.6*</td>
<td>59.5±2.8*</td>
<td>46.4±3.4*</td>
<td>37.1±3.5</td>
<td>23.9±4.9*</td>
<td>28.2±11.8</td>
<td>13.2±1.9*</td>
<td>28.9±4.7</td>
<td>0.042±0.015</td>
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<tr>
<td>LPD (n = 8)</td>
<td>30.9±4.5</td>
<td>149±24</td>
<td>16.5±5</td>
<td>51.5±5</td>
<td>37.5±5</td>
<td>35.3±5</td>
<td>37.7±5.8</td>
<td>24.0±5.2</td>
<td>14.5±1.4</td>
<td>29.5±2.4</td>
<td>0.041±0.018</td>
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<tr>
<td>+Glycine</td>
<td>33.2±5.6</td>
<td>136±38</td>
<td>28±7*</td>
<td>63±8*</td>
<td>50±8*</td>
<td>36±3</td>
<td>37.5±10</td>
<td>29.7±5.0</td>
<td>13.0±1.4*</td>
<td>31.0±6.0</td>
<td>0.049±0.022*</td>
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<tr>
<td>LPD + CAP (n = 6)</td>
<td>36.9±9.8</td>
<td>156±40</td>
<td>14.9±0.9</td>
<td>46±2</td>
<td>34±1</td>
<td>31.2±2.8†</td>
<td>36.3±10</td>
<td>22.1±5.5</td>
<td>11.9±0.9</td>
<td>26.8±0.8</td>
<td>0.055±0.023†</td>
</tr>
<tr>
<td>+Glycine</td>
<td>41±15</td>
<td>177±62</td>
<td>22.7±4.8*</td>
<td>58±7*</td>
<td>45±3*</td>
<td>34.7±3.1*</td>
<td>26.2±10.2</td>
<td>20.8±8.0</td>
<td>13.6±1.1*</td>
<td>29.4±1.8*</td>
<td>0.052±0.026</td>
</tr>
</tbody>
</table>

Values are means ± SE. LPD, low-protein diet; CAP, captopril; SNGFR, single-nephron glomerular filtration rate; SNBF, single-nephron blood flow; P_T, hydrostatic pressure with free flow; P_G, glomerular hydrostatic pressure; ΔP, transcapillary hydrostatic pressure gradient; π_A, afferent oncotic pressure; π_E, efferent oncotic pressure; P_SG, hydrostatic pressure with stop flow; AR, arteriolar resistance; ER, efferent arteriolar resistance; LpA, glomerular ultrafiltration coefficient. * P < 0.05 baseline vs. glycine. †P < 0.05 ANOVA, baseline values different from normal diet.
Analysis of proximal tubular reabsorption in 30 nephrons revealed that LPD was associated with significantly higher APR (13.8 ± 3.3 vs. 8.8 ± 3.2 nl/min, P < 0.05) and FR (0.46 ± 0.07 vs. 0.34 ± 0.06, P < 0.05) values compared with control in baseline conditions. Glycine infusion significantly reduced proximal tubular reabsorption (Fig. 1). In contrast to the changes observed in control rats and despite absence of changes in SNGFR (30.7 ± 4.6 vs. 32.5 ± 5.7 nl/min, ns), glycine infusion was associated with a significant reduction in proximal reabsorption expressed as absolute (13.8 ± 3.3 vs. 9.7 ± 4.1 nl/min, P < 0.01) or fractional values (0.46 ± 0.07 vs. 0.30 ± 0.13 nl/min, P < 0.01).

LPD + Captopril

The addition of captopril, an ACE inhibitor, did not produce significant changes in baseline glomerular hemodynamics compared with LPD with the exception of lower values for ΔP compared with both control and LPD rats (P < 0.025) and πA (P = 0.011). LpA values were significantly higher in LPD + captopril compared with control rats (P = 0.019). Arterial pressure remained constant during glycine infusion (114 ± 2 to 110 ± 1 mmHg). Glycine did not significantly modify GFR (3.2 ± 0.7 to 3.3 ± 0.5 ml/min), SNGFR (36.9 ± 9.8 vs. 41 ± 15 nl/min), and SNBF (156 ± 40 vs. 177 ± 62 nl/min). Again, the urinary flow rate increased significantly with glycine infusion (7 ± 1 to 41 ± 25 μl/min, P < 0.005). These fivefold increases in urine flow rate are comparable in all three groups despite differences in baseline values and differences in GFR. Significant increases were observed in P50 (46.1 ± 0.9 vs. 57.5 ± 2.4 mmHg), P2 (14.9 ± 0.9 vs. 22.7 ± 4.8 mmHg), and ΔP (31.2 ± 2.8 vs. 34.7 ± 3.1 mmHg). A significant reduction was observed in AR (36.3 ± 10.0 vs. 26.2 ± 10.2 Gdyne·s·cm⁻³) in the absence of significant changes in ER (22.1 ± 5.5 vs. 20.8 ± 8.0 Gdyne·s·cm⁻³).

At the level of the proximal tubule, neither absolute nor fractional tubular reabsorption was modified by glycine infusion in this group of rats (Fig. 1).

NM CMd Protein Expression

Figure 2 shows a representative Western blot for NMDA. The expression of NMDA is significantly lower in kidneys from rats fed the LPD for 2 wk (lanes 5–7: 2.104 ± 191 relative density units) when compared with control-diet animals (lanes 1–4: 3.444 ± 175 relative density units, P < 0.005). β-Actin levels were not different between groups (Fig. 2, bottom). Therefore, when normalized to β-actin, values are 4.484 ± 845 for control, and 2.642 ± 827 for LPD (P < 0.02). Brain levels of NMDA did not change between groups (data not shown).

DISCUSSION

Clearly, amino acids are no longer viewed as merely building blocks for proteins, and they have been known for some years to exert functional effects via specific receptors. In fact, glycine infusion produces major increases in glomerular filtration via renal vasodilation (4, 17). It is also well known that periodic high-protein calorie intake induces vasodilation in the kidney probably for the purpose of excretion of metabolic products of this protein calorie load (24). Previous studies in our laboratory examining the renal response to glycine administration both in normal conditions and in various disease models have established a reproducible pattern suggesting the presence of separate glomerular and tubular components in the response to glycine (4–7, 9, 10). Increases in GFR during glycine require renal vasodilation and parallel increases in absolute proximal tubular reabsorption to match the increase in nephron filtration rate such that FR is well maintained. Absence of a glomerular response has correlated so far with reductions in tubular reabsorption during glycine infusion. We postulated that the decrease in tubular reabsorption during glycine increase is a distal delivery to the macula densa and activates tubuloglomerular feedback, which prevents any further increases in nephron filtration rate.

The results of the current study support previous findings by us and other investigators demonstrating that glycine infusion increases GFR by a plasma flow-dependent mechanism. Indeed, glycine led to reductions in afferent and efferent arteriolar resistances with a subsequent increase in SNBF. Glomerular capillary pressures were not modified by glycine.

The mechanism by which glycine decreases glomerular resistances is not completely understood. Previous studies in our laboratory showed that inhibition of NO with nonspecific NOS blockers (N⁵-monomethyl-l-arginine) prevents the vasodilation and increase in GFR associated with glycine, suggesting that NO plays an important role as modulator/effector of the glycine response. We showed more recently that glycine-induced renal vasodilation is suppressed with NMDA antagonists (11). Taken altogether, these results suggest that activation of the NMDA receptor by glycine in the kidney may lead to vasodilation mediated by NO effects in the kidney or indirectly by modifying ANG II activity as we previously proposed (4).

The findings of the current study provide further evidence supporting the role of the renal NMDA receptor in glycine-induced renal vasodilation by demonstrating that downregulation of the receptor with LPD is associated with loss of the renal vasodilatory response to glycine. Close examination of the determinants of the glomerular hemodynamic process in LPD rats did not demonstrate any significant differences between LPD and control rats. However, these results present a conundrum with the previously published results wherein we demonstrated decreased baseline renal blood flow in rats given acute NMDA antagonists, yet the rats in the current study that have decreased NMDA receptors via LPD did not show a difference in baseline hemodynamics vs. control-diet rats. These findings reveal some of the complexities of this system. The previously published studies were undertaken by administration of the NMDA antagonists in acute experiments in which all the receptors are blocked with a pharmacological agent, whereas studies described herein were chronic studies.
where 50% of receptors were downregulated, at least as far as protein expression, by a LPD. It is likely that these factors that change during the 2-wk adaptation to the LPD and these may contribute to the seemingly disparate results.

The results of the current study stress the potential role of the NMDA receptor in modulating proximal tubular reabsorption, because downregulation of the receptor correlates with a decrease in absolute and fractional proximal reabsorption during glycine administration (although the baselines are shifted up). The reduction in proximal reabsorption during glycine in LPD rats is similar to the reduction in proximal reabsorption we previously observed in various experimental conditions characterized by absence of vasodilatory response to glycine including Goldblatt hypertension, experimental diabetes, cyclosporine administration, and chronic glomerulonephritis (6, 7, 9, 10). During low-protein feeding, as in the models previously mentioned, the decrease in proximal reabsorption increases delivery of sodium chloride to macula densa, thereby activating tubuloglomerular feedback and preventing or nullifying any potential vasodilatory response.

The current study demonstrates that the NMDA receptor subunit expression is downregulated after 2 wk of low-protein feeding. The mechanism by which diet affects NMDA receptor regulation is unknown; however, it may be related to amino acid content of the diet. Very little is known about the activation of the NMDA receptor complex or its regulation in the kidney. However, there is a large body of literature on the activation of the NMDA receptor complex or its regulation in the central nervous system, which may provide insights into the role in kidney function (3, 20, 22, 25, 28).

The NMDA receptor has been localized to various regions of the brain but has not been widely described outside of the central nervous system. Recently, we showed the NMDA receptor is constitutively expressed in the rat kidney (11). Leung and co-workers (19) confirmed the presence of NMDA receptors (both NR1 and NR2C subunits) in rat kidney. They also identified NMDA in LLC-PK1 and opossum kidney cells, both derived from proximal tubules, as well as Madin-Darby canine kidney cells, which are derived from distal tubules. Recently, we identified all four known NR2 subunits in rat kidney by Western blot analysis and by RT-PCR (29, 30). After 2-wk LPD, the NR2 A, B, and C subunits were all affected, whereas NR2D is not changed (29, 30). The implications are that diet may have multifaceted effects on regulation of the NMDA receptor and the glycine response and further suggest the importance of the NMDA receptor to kidney function.

The current findings clearly demonstrate that the NMDA NR1 receptor subunit expression is downregulated after 2 wk of low-protein feeding. The mechanism by which diet affects NMDA receptor regulation is unknown; however, it may be related to amino acid content of the diet. Very little is known about the activation of the NMDA receptor complex or its regulation in the kidney. However, there is a large body of literature on the activation of the NMDA receptor complex or its regulation in the central nervous system, which may provide insights into the role in kidney function (3, 20, 22, 25, 28).

In conclusion, glycine-induced vasodilation was abolished after 2 wk of LPD in rats, possibly due to decreases in absolute proximal reabsorption. In contrast to other models studied, captopril treatment did not completely restore this response. Coincident with the effects of glycine on vasodilation, LPD also downregulated kidney NMDA receptors. These studies indicate that the renal NMDA receptor may be a critical element in protein/amino acid-induced vasodilation.

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