Hemodynamic and Hormonal Changes to Dual Renin–Angiotensin System Inhibition in Experimental Hypertension


Abstract—We examined the antihypertensive effects of valsartan, aliskiren, or both drugs combined on circulating, cardiac, and renal components of the renin–angiotensin system in congenic mRen2.Lewis hypertensive rats assigned to: vehicle (n=9), valsartan (via drinking water, 30 mg/kg per day; n=10), aliskiren (SC by osmotic mini-pumps, 50 mg/kg per day; n=10), or valsartan (30 mg/kg per day) combined with aliskiren (50 mg/kg per day; n=10). Arterial pressure and heart rate were measured by telemetry before and during 2 weeks of treatment; trunk blood, heart, urine, and kidneys were collected for measures of renin–angiotensin system components. Arterial pressure and left-ventricular weight/tibia length ratio were reduced by monotherapy of valsartan, aliskiren, and further reduced by the combination therapy. Urinary protein excretion was reduced by valsartan and further reduced by the combination. The increases in plasma angiotensin (Ang) II induced by valsartan were reversed by the treatment of aliskiren and partially suppressed by the combination. The decreases in plasma Ang-(1–7) induced by aliskiren recovered in the combination group. Kidney Ang-(1–12) was increased by the combination therapy whereas the increases in urinary creatinine mediated by valsartan were reversed by addition of aliskiren. The antihypertensive and antiproteinuric actions of the combined therapy were associated with marked worsening of renal parenchymal disease and increased peritubular fibrosis. The data show that despite improvements in the surrogate end points of blood pressure, ventricular mass, and proteinuria, dual blockade of Ang II receptors and renin activity is accompanied by worsening of renal parenchymal disease reflecting a renal homeostatic stress response attributable to loss of tubuloglomerular feedback by Ang II. (Hypertension. 2013;61:417–424.)

Key Words: angiotensin-(1–12) • aliskiren • arterial remodeling • direct renin inhibitors • urinary protein • valsartan

The lessons learned from studies in humans and animals using angiotensin-converting enzyme (ACE) inhibitors showed the existence of alternate mechanisms for angiotensin II (Ang II) generation, through either ACE escape or direct conversion of Ang I to Ang II by chymase. These findings led to exploring the utility of therapies in which ACE inhibitors and Ang II type 1 receptor (AT1R) blockers were combined to optimize renin–angiotensin system (RAS) blockade. Although the rationale for blocking the system at multiple foci was compelling, the increased risk of acute dialysis and hyperkalemia found in the Ongoing Telmisartan Alone and in Combination with Ramipril Global Endpoint Trial (ONTARGET) discouraged this therapeutic approach. The introduction of an orally active direct renin inhibitor created an opportunity to bypass the large reactive increase in renin secretion induced by interruption of the Ang II negative feedback on renin release. Although aliskiren hemifumarate, the first orally effective direct renin inhibitor for the treatment of hypertension, showed efficacy as an antihypertensive agent and in target organ protection, it failed to suppress Ang II formation as the valsartan–aliskiren combination was more effective than each drug alone. Enthusiasm for combined blockade of either ACE inhibitors or direct renin inhibitor with AT1R blocker is now further questioned given the recent halting of the Aliskiren Trial in Type 2 Diabetes Using Cardiovascular and Renal Disease Endpoints (ALTITUDE) trial, in which patients receiving the combination of aliskiren with either valsartan or an ACE inhibitor (http://www.theheart.org/article/1331173.do) experienced an increased incidence of nonfatal stroke, renal complications, hyperkalemia, and hypertension over 18 to 24 months of follow-up.
The complexity of the physiological mechanisms that participate in the expression of angiotensin peptides is further underscored by the identification of an extended form of Ang I, proangiotensin 12 [Ang-(1–12)], by Nagata et al. Evidence that Ang-(1–12) acts as an alternate pathway for Ang II production in rodents and human tissue led us to conduct a rigorous investigation of the effect of combining aliskiren with valsartan on blood pressure, the circulating and tissue RAS, and renal excretory function. These studies were done in a congenic model of hypertension expressing increased tissue renin.

Methods

Animals
Experiments in male 10-week-old mRen2.Lewis rats were performed in accordance with National Institutes of Health guidelines and were approved by the Wake Forest University animal care and use committee.

Arterial Pressure, Heart Rate, and Locomotive Activity Measurements
Continuous measures of arterial pressure and heart rate were obtained from telemetry probes chronically implanted as reported previously. Delta mean arterial pressure (MAP) changes were calculated as the difference between the 3-day MAP averages obtained during the baseline period and the 7-day MAP average during the last treatment-week.

Treatment Protocol
After a 2-week recovery period from telemetry probe implantation, rats were randomized to receive either (1) vehicle, (2) valsartan (30 mg/kg per day), (3) aliskiren (50 mg/kg per day), or (4) both drugs (valsartan 30 mg/kg per day) and aliskiren (50 mg/kg/day)). Valsartan was given in the drinking water, and aliskiren was subcutaneously delivered by osmotic mini-pumps (ALZET model 2ML2; DURECT Corp., Cupertino, CA). Pumps containing saline were implanted to vehicle and valsartan groups. After 2 weeks of treatment, animals were decapitated and trunk blood, heart, and kidneys were collected and processed as previously described. Doses of aliskiren alone or combined with valsartan were shown to reverse hypertension and cardiac hypertrophy in both transgenic mRen227 and congenic mRen2.Lewis hypertensive rats. Valsartan and aliskiren were a kind gift from Novartis, Inc.

Biochemistry
Plasma renin activity (PRA), defined as the rate of Ang I generation from endogenous substrate, was measured in incubated plasma treated with EDTA and phenylmethylsulfonyl fluoride to prevent the degradation of the generated peptide. Plasma renin concentration was defined as the rate of Ang I generation from renin in samples incubated at pH 6.5 for 90 minutes with excess exogenous angiotensinogen obtained from nephrectomized rat plasma. Valsartan was given in the drinking water, and aliskiren was subcutaneously delivered by osmotic mini-pumps (ALZET model 2ML2; DURECT Corp., Cupertino, CA). Pumps containing saline were implanted to vehicle and valsartan groups. After 2 weeks of treatment, animals were decapitated and trunk blood, heart, and kidneys were collected and processed as previously described. Doses of aliskiren alone or combined with valsartan were shown to reverse hypertension and cardiac hypertrophy in both transgenic mRen227 and congenic mRen2.Lewis hypertensive rats. Valsartan and aliskiren were a kind gift from Novartis, Inc.

Analysis of Gene Expression by Quantitative Real-Time Polymerase Chain Reaction
Real-time polymerase chain reaction was performed to detect cardiac and renal mRNA expression levels for ACE and ACE2 in group a, b, and d as described previously. Sequence-specific oligonucleotide primers were designed according to published GenBank (www.ncbi.nlm.nih.gov/Genbank) sequences. Expression levels are given relative to the geometric mean of the control group.

Statistical Analysis
All values are expressed as mean±SEM. MAP and urinary parameters were analyzed by 2-way ANOVA followed by the Bonferroni post hoc test. Other data were analyzed by 1-way ANOVA followed by the Turkey post hoc test. All data were analyzed using GraphPad PRISM (GraphPad, San Diego, CA) with P<0.05 considered statistically significant.

Results
The reductions in MAP induced by the combination therapy were greater than those produced by valsartan or aliskiren monotherapy (Figure 1). No treatment had an effect on heart rate. Although all 3 treatments reduced whole heart weight/tibia length (TL) ratio and left-ventricular weight/TL ratios compared with vehicle-treated mRen2.Lewis rats (Table 1), the combination treatment reduced left-ventricular weight/TL ratio more than each agent alone (Table 1). On the contrary, the combination of valsartan/aliskiren increased kidney weight/body weight and kidney weight/TL ratios by 14% and 11%, respectively, when compared with vehicle (Table 1).

Effects of Valsartan, Aliskiren, and Combination Therapy on RAS Components
Figure 2 shows the effects of the treatments on systemic RAS components. Valsartan and combination therapy increased PRA compared with vehicle and aliskiren. Combination therapy increased plasma renin concentration by 14-fold compared with vehicle and this change contrasted markedly with the reductions in PRA/plasma renin concentration ratio found in rats treated with either aliskiren or valsartan alone. Only the combination therapy induced increases in plasma Ang I levels, whereas the large increases in plasma Ang II produced by valsartan were suppressed in rats medicated with aliskiren and partially reversed during combination therapy (Figure 2). Aliskiren reduced plasma Ang-(1–7) level compared with other groups. Plasma Ang-(1–7)/Ang II ratio was highest in the aliskiren group. Plasma Ang-(1–12) and tissue RAS components in group a, b, and d are shown in Table S1 in the
online-only Data Supplement. There were no differences in plasma Ang-(1–12) levels among the 3 groups. Tissue concentrations of Ang-(1–12), Ang II, and Ang-(1–7) in the left ventricle were not different among rats given vehicle, valsartan, or the combined therapy (Table S1). On the contrary, kidney cortex content of Ang-(1–12) was higher in rats given the combination therapy compared with valsartan-treated rats, whereas both valsartan and the combination therapy led to marked decreases in renal Ang II content (Table S1). The treatments had no effect on renal Ang-(1–7) content (Table S1).

Exposure to either valsartan or the combination therapy had no effect on the cardiac expression of ACE and ACE2 mRNAs. Renal cortex ACE2 gene expression was not altered by valsartan and decreased in rats medicated with valsartan/aliskiren.

Figure S1 shows a marked reduction in the urinary excretion of Aogen by valsartan, aliskiren, or valsartan/aliskiren when compared with baseline values obtained either before initiation of treatment or the vehicle-treated groups. Urinary Ang-(1–12) excretion was similarly reduced by valsartan and the combination therapy and not changed in rats receiving aliskiren. Only aliskiren reduced urinary Ang II levels compared with valsartan. The decreases in urinary Ang-(1–7) excretion were similarly reduced in rats medicated with valsartan, aliskiren, or valsartan/aliskiren. In addition, urinary protein/creatinine ratio correlated positively with kidney Ang II level and negatively with kidney Ang-(1–7)/Ang II ratio (Figure S2).

Effects of RAS Blockade on Renal Excretory Function

The effects of treatments on renal excretory function are shown in Table 2. All drug-treatments caused a mild reduction in water intake and comparative decreases in urinary output. Although valsartan or aliskiren increased urinary creatinine levels, the combination treatment reversed these changes. Twenty-four-hour urinary protein excretion was decreased only in the combination group, whereas urinary protein/creatinine ratio was reduced in valsartan and the combination group but not in rats medicated with aliskiren. Moreover, the values of urinary protein/creatinine ratio in the combination group were significantly lower than that in aliskiren group. Serum urea nitrogen and potassium was augmented only in rats medicated with aliskiren or the combined treatment.

Renal Histological Changes Induced by the Treatments

Representative changes of the alterations present in the kidney of vehicle-treated mRen2.Lewis hypertensive rats and of those receiving valsartan, aliskiren, or the combined treatment are

Table 1. Effects of Treatments on Heart and Kidney Weight

<table>
<thead>
<tr>
<th>Variable</th>
<th>Vehicle (n=9)</th>
<th>Valsartan (n=10)</th>
<th>Aliskiren (n=10)</th>
<th>Combination (n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHW/BW, mg/g</td>
<td>3.85±0.06</td>
<td>3.10±0.03*</td>
<td>3.25±0.08*</td>
<td>3.02±0.04*†</td>
</tr>
<tr>
<td>WHW/TL, mg/mm</td>
<td>36.8±0.5</td>
<td>29.0±0.4*</td>
<td>30.7±0.2*,‡</td>
<td>28.1±0.4*§</td>
</tr>
<tr>
<td>LWB/BW, mg/g</td>
<td>2.74±0.04</td>
<td>2.10±0.03*</td>
<td>2.16±0.05*</td>
<td>1.97±0.03*§</td>
</tr>
<tr>
<td>LWB/TL, mg/mm</td>
<td>26.2±0.41</td>
<td>19.6±0.24*</td>
<td>20.4±0.20*</td>
<td>18.3±0.29*§</td>
</tr>
<tr>
<td>KW/BW, mg/g</td>
<td>3.82±0.05</td>
<td>3.95±0.10</td>
<td>4.17±0.12</td>
<td>4.35±0.11‖‡</td>
</tr>
<tr>
<td>KW/TL, mg/mm</td>
<td>36.5±0.4</td>
<td>39.9±0.9</td>
<td>39.5±1.1</td>
<td>40.5±0.9§‖‡</td>
</tr>
</tbody>
</table>

WHW indicates whole heart weight; BW, body weight; TL, tibia length; LWB, left-ventricular weight; and KW, kidney weight. Values are mean±SEM.

*P<0.001 vs vehicle.
†P<0.05 vs aliskiren.
‡P<0.05 vs valsartan.
§P<0.001 vs valsartan.
‖P<0.01 vs vehicle.
¶P<0.05 vs vehicle.

Figure 1. Time course of changes in mean arterial pressure (MAP) in response to administration of vehicle, valsartan, aliskiren, and valsartan/aliskiren (top) and changes in mean arterial pressure from baseline (bottom). Values are means±SEM. ***,†††,### P<0.001 vs vehicle, ††P<0.001 vs valsartan, ##P<0.01 vs aliskiren.
with all 3 treatments, especially with the combination of valsartan/aliskiren. We suggest that these new findings reflect the kidneys inability to autoregulate renal blood flow after the relative hypotension and blockade of the actions of Ang II on tubuloglomerular feedback mechanisms. We further suggest that the larger antihypertensive response produced by the combination therapy may make the kidneys more susceptible to hypoperfusion leading to regional tissue ischemia and fibrosis. In keeping with this interpretation, Gomez et al23–25 showed that progression of renal disease is associated with deterioration of the kidney microvasculature and the reenactment of embryonic pathways, features that were present in the kidney of valsartan/aliskiren treated rats. In agreement with these findings, a previous study showed no additional renoprotective actions of the combination therapy in m(Ren2)27 transgenic hypertensive rats.26 Thus, these new results agree with clinical findings in which a multiloci blockade of RAS components has a detrimental impact on renal function despite the apparent beneficial effects on surrogate end points such as blood pressure and proteinuria. Altogether, the detailed characterization of the effects of valsartan/aliskiren over those induced by valsartan or aliskiren alone is in keeping with emerging data demonstrating that blockade of AT1Rs together with either ACE or renin inhibition may negate the beneficial effects of selective blockade of one of these pathways.2,3,7,26,27

As an experimental model of hypertension, the mRen2. Lewis rat retains the increased tissue renin transgene expression derived from the backcross of the original m(Ren2)27 transgenic hypertensive rat.15 The use of telemetry for assessment of the effects of therapies on blood pressure and heart rate, a comprehensive quantitative evaluation of changes in RAS components using procedures firmly established in our laboratory, and an independent and blind assessment of histological findings are additional strengths of the reported research. Although the generalizability of our findings to human hypertensive disease has obvious limitations, our data
provide a window for understanding why dual RAS inhibition may negate clinically the beneficial effects of selective blockade of Ang II or renin.2,3,7,26,27

The demonstration that valsartan/aliskiren reduced arterial pressure more than valsartan or aliskiren alone in mRen2. Lewis hypertensive rats agrees with previous human and animal findings.5 Partial blunting of the increased plasma Ang II induced by valsartan and recovery of reduced plasma Ang-(1–7) induced by aliskiren in the combination group may explain the stronger antihypertensive and cardiac antihypertrophic actions of the combination therapy. Overall, the effects of the treatments on plasma and tissue RAS components agree with the existence of separate regulatory expression of the components in the circulating and tissue compartments. In this study, the increases in both plasma Ang I and serum ACE activity induced by the combined treatment

Table 2. Renal Excretory Response to the Treatments

<table>
<thead>
<tr>
<th>Variable</th>
<th>Vehicle (n=9)</th>
<th>Valsartan (n=10)</th>
<th>Aliskiren (n=10)</th>
<th>Combination (n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water intake, mL</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Baseline</td>
<td>32.0±1.2</td>
<td>30.7±1.7</td>
<td>32.6±3.3</td>
<td>30.9±1.1</td>
</tr>
<tr>
<td>2-wk</td>
<td>37.0±2.4</td>
<td>24.0±1.0†</td>
<td>23.7±1.2*</td>
<td>26.1±0.6*‡</td>
</tr>
<tr>
<td>Urine volume, mL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>20.7±1.1</td>
<td>20.4±1.2</td>
<td>19.9±3.2</td>
<td>20.4±1.5</td>
</tr>
<tr>
<td>2-wk</td>
<td>23.7±2.9</td>
<td>14.8±0.4§</td>
<td>14.2±0.9§</td>
<td>15.4±0.7*</td>
</tr>
<tr>
<td>Urine creatinine, mg/dL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>70.8±7.7</td>
<td>67.1±7.0</td>
<td>74.3±7.1</td>
<td>70.6±8.2</td>
</tr>
<tr>
<td>2-wk</td>
<td>88.0±9.1</td>
<td>126.3±10.8§</td>
<td></td>
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<tr>
<td>Urine protein, mg/24 h</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>21.0±2.1</td>
<td>20.5±1.7</td>
<td>23.3±2.8</td>
<td>21.7±2.0</td>
</tr>
<tr>
<td>2-wk</td>
<td>23.8±1.9</td>
<td>17.9±2.3</td>
<td>23.5±3.1</td>
<td>10.7±0.9*§</td>
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<tr>
<td>Protein/creatinine, mg/mg/24 h</td>
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<td></td>
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<tr>
<td>Baseline</td>
<td>32.1±4.1</td>
<td>33.6±4.3</td>
<td>31.8±2.9</td>
<td>32.4±3.5</td>
</tr>
<tr>
<td>2-wk</td>
<td>25.9±1.7</td>
<td>14.8±2.1**‖</td>
<td>23.7±3.4</td>
<td>11.4±0.8‡†‖</td>
</tr>
<tr>
<td>Serum urea nitrogen, mg/dL</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2-wk</td>
<td>35.8±2.7</td>
<td>38.0±1.0</td>
<td>44.9±2.1**</td>
<td>46.0±2.4§‖</td>
</tr>
<tr>
<td>Serum creatinine, mg/dL</td>
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<tr>
<td>Baseline</td>
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<td>NA</td>
<td>NA</td>
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</tr>
<tr>
<td>2-wk</td>
<td>0.45±0.03</td>
<td>0.42±0.03</td>
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<td>0.51±0.04</td>
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<td>Serum Na+, mmol/L</td>
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<td>Baseline</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2-wk</td>
<td>140.3±3.6</td>
<td>138.5±1.3</td>
<td>139.0±2.4</td>
<td>138.9±0.8</td>
</tr>
<tr>
<td>Serum K+, mmol/L</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
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<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2-wk</td>
<td>6.07±0.19</td>
<td>6.55±0.16</td>
<td>6.83±0.13§</td>
<td>7.02±0.16**</td>
</tr>
<tr>
<td>Creatinine clearance, mL/min</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2-wk</td>
<td>2.83±0.25</td>
<td>3.49±0.63</td>
<td>2.37±0.18</td>
<td>2.09±0.21</td>
</tr>
</tbody>
</table>

NA indicates not applicable. Values are means±SEM.
*P<0.001 vs vehicle.
†P<0.05 vs basal.
‡P<0.01 vs basal.
§P<0.01 vs vehicle.
‖P<0.001 vs basal.
¶P<0.05 vs valsartan.
#P<0.001 vs aliskiren.
**P<0.05 vs vehicle.
††P<0.05 vs aliskiren.
may reflect a compensatory rise in renin secretion attributable to blockade of the AT1R-mediated negative feedback to renin production. Because the increased serum ACE activity was associated with a reduction in the plasma Ang II/Ang I ratio, these data confirm that the combination of valsartan/aliskiren causes an upregulation of circulating ACE. Aliskiren is reported to have high affinity with human and mouse renin but very low affinity with rat renin. Because of the release of the negative feedback from AT1R, the combined therapy of valsartan/aliskiren causes a reactive rise in secretion of rat renin, which is much less susceptible to inhibition by aliskiren as reported in m(Ren2)27 transgenic hypertensive rats. In addition, this reactively increased renin acts to attenuate the suppression of Ang I by aliskiren. The demonstration of increased number of renin cells in the afferent arterioles of the treated groups (Figure 5) agrees with the observed increases in PRA, plasma renin concentration, and plasma Ang I found with the combination therapy. On the contrary, the large increases in Ang I mediated by the combination therapy did not result in augmented plasma Ang II levels because aliskiren effectively suppressed the increases in plasma Ang II levels induced by valsartan. This may be explained through increased ACE2 activity by aliskiren, reflecting the increase in plasma Ang-(1–7)/Ang II ratio.
The existence of nonrenin-dependent pathways for angiotensin peptides formation led us to determine the effect of the treatments on plasma, cardiac, and renal concentrations of Ang-(1–12). Recent studies from this laboratory showed that both ACE and chymase account for the production of Ang II from Ang-(1–12). Measurements of Ang-(1–12) in plasma and cardiac tissue confirmed that its presence is not altered by administration of the treatments, additional evidence for its independent regulation from renin. The increase in renal Ang-(1–12) induced by the combination therapy compared with valsartan-treated rats suggest that renin inhibition upregulates alternative processing of Aogen to Ang-(1–12) by an as-yet-to-be-identified enzymatic pathway. Further work is necessary to determine whether the increases in Ang-(1–12) might be associated with the worsening of kidney injury.

The effects of the therapies on renal cortex content of the angiotensins showed a significant reduction of Ang II in both valsartan and valsartan/aliskiren-treated rats. Consistently, Kobori et al showed that Aogen is produced in proximal tubular cells as well as in the liver and also found that systemic Ang II infusion increases Aogen in kidney and urine. The decrease of renal ACE2 mRNA in the combination group may be explained by the worsening of renal parenchymal disease as reported in human renal biopsies from patients with chronic kidney disease.

We conclude that whereas the combination of valsartan/aliskiren exerted a greater effect in reducing blood pressure, cardiac hypertrophy, and proteinuria, improvements in these surrogate end points is associated with aggravation of renal disease. The discrepant results in terms of the surrogate end points of blood pressure, cardiac hypertrophy, and proteinuria compared with the morphological changes in the kidney provide now a mechanistic window for understanding the adverse clinical outcomes reported with the use of dual RAS inhibitors.

**Perspective**

The theoretical advantages of dual inhibition of RAS components using ACE or direct renin inhibitors with AT,R blockers is a logical approach for the management of hypertension as they act synergistically in suppressing the reactive rise in PRA resulting from blockade of AT,Rs. Although previous studies in animals and hypertensive subjects suggested that such combinations favorably affect blood pressure, adverse cardiac remodeling, and proteinuria, their long-term effects on renal function and clinical events has failed to support the merits of this therapeutic combination. Our detailed investigation of the effect of combination therapy with valsartan and aliskiren in a renin-dependent hypertension model showed a significant discrepancy among the merit of this combination in terms of the surrogate end points of blood pressure, cardiac hypertrophy, and proteinuria and the progression of hypertension-induced renal damage. The results of this study suggest that dual blockade of renin activity and AT,Rs prevents the activation of intrinsic renoprotective mechanisms to compensate for the decreases in renal perfusion pressure.

**Sources of Funding**

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**Disclosures**

Dr Ferrario is the recipient of a grant from Novartis, Inc. He is also a member of the Novartis Advisory Board. The other authors have no conflicts to report.

**References**


4. Kobori et al showed that Aogen is produced in proximal tubular cells as well as in the liver and also found that systemic Ang II infusion increases Aogen in kidney and urine. The decrease of renal ACE2 mRNA in the combination group may be explained by the worsening of renal parenchymal disease as reported in human renal biopsies from patients with chronic kidney disease.

5. Moniwa et al showed that Aogen is produced in proximal tubular cells as well as in the liver and also found that systemic Ang II infusion increases Aogen in kidney and urine. The decrease of renal ACE2 mRNA in the combination group may be explained by the worsening of renal parenchymal disease as reported in human renal biopsies from patients with chronic kidney disease.


Novelty and Significance

What Is New?
• The first direct demonstration in an experimental model of renin-dependent hypertension that the merits of combining the AT1 receptor antagonist valsartan with a direct renin inhibitor aliskiren is associated with worsening of renal parenchymal disease despite the beneficial effects of this treatment on blood pressure, cardiac hypertrophy, and proteinuria.

What Is Relevant?
• These experimental findings now provide an explanation for the absence of any additional cardiovascular protection and even worsening of renal function during dual blockade of the renin–angiotensin system.

Summary
Our studies in mRen2.Lewis congenic hypertensive rats medicated with valsartan, aliskiren, or the combination of valsartan/aliskiren demonstrated that the additional antihypertensive and antiproteinuric effect of preventing a reactive rise in plasma renin activity does not suppress cardiac content of angiotensin peptides while markedly lowering the renal content of angiotensin (Ang) II but not Ang-(1–7). In addition, the combination therapy is associated with a mild increase in renal cortical content of Ang-(1–12) as well as causing large decreases in urinary excretion rates of angiotensinogen, Ang-(1–12), and Ang-(1–7). The deactivation of renin–angiotensin system components in the kidney of valsartan/aliskiren-treated rats is associated with worsening of renal parenchymal disease above the structural changes that are induced by the hypertensive process in the vehicle-treated rats.
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ONLINE SUPPLEMENT

Hemodynamic and Hormonal Changes to Dual Renin Angiotensin System Inhibition in Experimental Hypertension

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Short Title: Combination of Valsartan/Aliskiren

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Supplemental Tables and Figures

**Table S1. Effects of treatments on RAS components in plasma, left ventricle and kidney cortex**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Vehicle (n=9)</th>
<th>Valsartan (n=10)</th>
<th>Combination (n=10)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plasma</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ang-(1-12), fmol/mL</td>
<td>159.5 ± 5.2</td>
<td>170.3 ± 10.1</td>
<td>173.6 ± 8.5</td>
</tr>
<tr>
<td><strong>Left ventricle</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ang-(1-12), fmol/mg protein</td>
<td>25.3 ± 2.7</td>
<td>20.6 ± 1.8</td>
<td>26.7 ± 3.1</td>
</tr>
<tr>
<td>Ang II, fmol/mg protein</td>
<td>16.1 ± 1.9</td>
<td>14.2 ± 1.5</td>
<td>16.2 ± 2.2</td>
</tr>
<tr>
<td>Ang-(1-7), fmol/mg protein</td>
<td>14.5 ± 1.6</td>
<td>15.7 ± 1.4</td>
<td>15.7 ± 1.9</td>
</tr>
<tr>
<td>ACE mRNA, units</td>
<td>1.00 ± 0.06</td>
<td>0.88 ± 0.03</td>
<td>0.81 ± 0.03</td>
</tr>
<tr>
<td>ACE2 mRNA, units</td>
<td>1.00 ± 0.06</td>
<td>0.85 ± 0.06</td>
<td>0.81 ± 0.07</td>
</tr>
<tr>
<td><strong>Kidney cortex</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ang-(1-12), fmol/mg protein</td>
<td>147.0 ± 17.0</td>
<td>134.8 ± 10.0</td>
<td>179.8 ± 8.9†</td>
</tr>
<tr>
<td>Ang II, fmol/mg protein</td>
<td>24.8 ± 2.3</td>
<td>12.9 ± 0.5***</td>
<td>12.0 ± 1.2***</td>
</tr>
<tr>
<td>Ang-(1-7), fmol/mg protein</td>
<td>12.9 ± 0.9</td>
<td>12.7 ± 0.5</td>
<td>13.0 ± 1.3</td>
</tr>
<tr>
<td>ACE mRNA, units</td>
<td>1.00 ± 0.10</td>
<td>1.11 ± 0.06</td>
<td>0.92 ± 0.06</td>
</tr>
<tr>
<td>ACE2 mRNA, units</td>
<td>1.00 ± 0.09</td>
<td>1.04 ± 0.07</td>
<td>0.75 ± 0.09†</td>
</tr>
</tbody>
</table>

Values are means ± SEM. mRNA values, relative gene expression as described in Methods. †: P<0.05 vs valsartan, ***: P<0.001 vs vehicle
**Figure S1.** Patterns of urinary excretion rates of angiotensinogen (Aogen), angiotensin-(1-12) [Ang-(1-12)], Ang II, and Ang-(1-7) in mRen2.Lewis rats medicated with valsartan, aliskiren, or the combination of valsartan/aliskiren. Values are means ± SEM. *: P<0.05 vs vehicle, #: P<0.05 vs before treatment, **: P<0.01 vs vehicle, ††: P<0.01 vs valsartan, ##:
P<0.01 vs before treatment, ###: P<0.001 vs before treatment.
Figure S2. Correlations between urinary protein/creatinine ratio and kidney Ang II level (left panel) or kidney Ang-(1-7)/Ang II ratio (right panel).