Comparative Study of Vasodilators in an Animal Model of Chronic Volume Overload Caused by Severe Aortic Regurgitation

Eric Plante, PhD; Dominic Lachance, MSc; Jonathan Beaudoin, MD; Serge Champetier, PhD; Élise Roussel, MSc; Marie Arsenault, MD; Jacques Couet, PhD

Background—Aortic regurgitation (AR) is a disease of chronic left ventricular (LV) volume overload. Over time, AR will lead to LV dilatation, hypertrophy, and loss of function. There is currently no medical treatment proven effective to slow the evolution of this cardiomyopathy. Vasodilators were once thought to have protective effects, but recent publications have cast some doubts about their effectiveness. We hypothesized that drugs targeting the renin-angiotensin system should be more effective than those having no direct effect on the renin-angiotensin system.

Methods and Results—We designed a protocol comparing the effects of 3 vasodilators in a rat AR model (n=9 to 11 animals per group). The effects of a 6-month treatment of (1) nifedipine, (2) captopril, or (3) losartan were compared in male AR rats. Sham-operated and untreated AR animals were used as controls. Nifedipine-treated animals displayed hemodynamics, LV dilatation, hypertrophy, and loss of function similar to those of the untreated group. Both captopril and losartan were effective in improving hemodynamics, slow LV dilatation, hypertrophy, and dysfunction. Gene expression analysis confirmed the lack of effects of the nifedipine treatment at the molecular level.

Conclusions—Using an animal model of severe AR, we found that vasodilators targeting the renin-angiotensin system were effective to slow the development of LV remodeling and to preserve LV function. As recently shown in the most recent human clinical trial, nifedipine was totally ineffective. Targeting the renin-angiotensin system seems a promising avenue in the treatment of this disease, and clinical trials should be carefully designed to re-evaluate the effectiveness of angiotensin I–converting enzyme inhibitors or angiotensin II receptor blockers in AR. (Circ Heart Fail. 2009;2:25-32.)

Key Words: heart diseases ■ valves ■ renin-angiotensin system ■ vasodilators

Chronic volume overload such as seen in severe aortic regurgitation (AR) causes a progressive dilatation and hypertrophy of the left ventricle. Paralleling this remodeling LV function eventually decreases, symptoms appear and valve replacement surgery often becomes necessary. Compared with other cardiac diseases, little is known about the treatment of chronic volume overload. In past decades, several investigators have reported that medical therapy with vasodilators may be effective to reduce the aortic regurgitant volume and help maintain left ventricular (LV) function. Nifedipine, a dihydropyridine calcium channel blocker, seemed to be an especially promising drug. However, a more recent trial has failed to confirm any positive effects of nifedipine or enalapril treatment compared with placebo. Considering these conflicting data, the AHA/ACC Valvular Heart Disease Treatment Guidelines no longer recommend any vasodilator for the medical management of chronic AR in patients with normal ventricular function. In summary, no drug has yet been clearly shown to be able to slow LV dilatation, hypertrophy, or loss of systolic function or have any impact on morbidity or mortality in chronic AR. Human clinical trials focusing on AR are unfortunately rare and usually include a limited number of patients with many confounding factors and pitfalls. The study of an animal model of a disease can help overcome some of those pitfalls and offer the added benefit of providing cardiac tissues for analysis.

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Our group has previously reported in an animal model of chronic AR that the renin-angiotensin system (RAS) is abnormally activated suggesting that blocking this system could play an important role in preventing LV dilatation, hypertrophy, and loss of systolic function. We have also shown in the same model that high doses of an angiotensin II converting enzyme inhibitor such as captopril seem to be able to protect against AR cardiomyopathy both in normotensive as well as hypertensive rats. Knowing that nifedipine does...
not target RAS, the current study was primarily designed to compare the effects of vasodilators targeting or not targeting RAS on the evolution of LV dilation, hypertrophy, and loss of systolic function. We hypothesized that RAS-targeting vasodilators would be the most effective.

Methods

Animal Model of AR

Sixty male Wistar rats (300 to 350 g; Charles River, Quebec, Canada) had severe AR induced by retrograde puncture of the aortic valve leaflets as previously described8,9 and randomly divided into 5 groups (n=10 to 11 per group) as follows: (1) normal sham-operated animals (Sham); (2) AR untreated (AR); (3) AR treated with nifedipine (AR-N) (75 mg/kg/d); (4) AR treated with captopril (AR-C) (1 g/L in drinking water); or (5) AR treated with losartan (AR-L) (10 mg/kg per day in drinking water). AR was considered severe by echocardiography by the presence of all of the following criteria at the time of surgery: color-Doppler ratio of regurgitant jet width to LVOT diameter >50%, retrograde holo-diatolic flow in proximal descending aorta with end-diastolic velocity >18 cm/s, ratio of time-velocity integral of reversed diastolic flow to forward systolic flow in descending thoracic aorta >60%, and acute increase in LV diastolic dimension during the surgical procedure. Echocardiographic criteria of AR severity had to be accompanied by an acute drop of aortic diastolic pressure of at least 30% to qualify. Animals not meeting the echographic and hemodynamic criteria were not included in the study. Drug treatments were started 2 weeks after the surgical procedure to allow for recovery from the acute phase and continued thereafter for 6 months. Animals were clinically evaluated daily by experienced animal laboratory technicians for the presence of signs of heart failure (increased respiratory rate/distress and/or peripheral edema) and were weighed weekly. At the end of the protocol, surviving animals were euthanized, hearts were quickly dissected, and all cardiac chambers were weighed. Left ventricles were snap-frozen in liquid nitrogen (LN2) and kept at −80°C for further analysis. This protocol was approved by the Université Laval’s Animal Protection Committee according to the recommendations of the Canadian Council on Laboratory Animal Care.

Echocardiography

A complete M-mode, 2D, and Doppler echocardiogram was performed on the animals under 1.5% isoflurane anesthesia after 6 months. At other times during the protocol, systolic and diastolic blood pressures were measured noninvasively using the tail-cuff method.

Statistical Analysis

Results are presented as mean±SEM unless specified otherwise. Intergroup comparisons were done using 1-way ANOVA and Tukey posttest. Statistical significance was set at a P<0.05. Data and statistical analysis were performed using Graph Pad Prism version 4.02 for Windows (Graph Pad Software, San Diego, Calif).

Statement of Responsibility

The authors had full access to and take full responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

Results

Clinical Data

All animals survived the duration of the protocol, except for 2 in the nifedipine group. Both deaths were sudden, un witnessed (occurred overnight) and were not accompanied by any symptoms or signs of impending heart failure in the preceding days. There were no signs of acute heart failure at necropsy in those 2 animals. Drugs were well tolerated. There was no clinical heart failure in any of the animals. Body weight was similar in all groups except for the captopril group in which the animals were smaller after 6 months (Table 2). Tibial length was also slightly shorter in the captopril group but this difference was minimal (<2%).
remained similar in all groups. Relative wall thickness was expected, untreated AR animals (NT) developed severe LV dilatation and lower ejection fraction. AR severity was similar in all AR groups. As expected, untreated AR had severe LV hypertrophy as shown by the LV mass data reported in Table 2. LV mass was compared with normal sham animals but less in the captopril group. Left atria were also larger in all AR groups. The largest left atria were found in the nifedipine group. Captopril and losartan had no impact on LA dilatation. Lung weights were similarly increased in all AR groups and drug treatment had no impact on that measurement.

Echocardiographic Data

The data obtained after 6 months of treatment are summarized in Table 3. AR severity was similar in all AR groups. As expected, untreated AR animals (NT) developed severe LV diastolic and systolic dilatation and lower ejection fraction when compared with normal sham controls. Wall thickness remained similar in all groups. Relative wall thickness was lower in untreated AR as expected in an eccentric pattern of LV remodeling. Results in the nifedipine group for LV dimensions, relative wall thickness, and ejection fraction were similar to those of the untreated AR group. However, captopril and losartan significantly decreased the end-systolic dimensions. Ejection fraction was significantly better in the captopril and the losartan groups compared with the nifedipine group. Relative wall thickness also tended to increase although this trend did not reach statistical significance. There was no significant difference between the results of the captopril and losartan groups.

Tissue Analysis

Hearts were explanted at the end of the protocol and cardiac chambers were weighed. Results are summarized in Table 2. As expected, untreated AR had severe LV hypertrophy as shown by the LV mass data reported in Table 2. LV mass was similarly increased in the nifedipine group as the untreated group and was lower in captopril and losartan-treated animals. Right ventricular weight was increased in all AR groups and drug treatment did not decrease cardiac output. However, cardiac output was high in the untreated AR group compared with normal shams. Nifedipine did not decrease cardiac output. However, cardiac output was significantly lower and closer to normal in both captopril and losartan groups because of a smaller stroke volume. AR increased systolic and decreased diastolic blood pressure thereby increasing pulse pressure as expected. Both captopril

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Sham (n=11)</th>
<th>NT (n=11)</th>
<th>Captopril (n=10)</th>
<th>Losartan (n=10)</th>
<th>Nifedipine (n=9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight, g</td>
<td>637±17.5</td>
<td>687±31.6</td>
<td>547±16.0*</td>
<td>694±14.9</td>
<td>653±17.8</td>
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<td>Tibial length, mm</td>
<td>59.7±0.37</td>
<td>60.0±0.32</td>
<td>58.7±0.42†</td>
<td>59.7±0.42</td>
<td>61.4±0.22†</td>
</tr>
<tr>
<td>Heart weight, mg</td>
<td>1348±37.1*</td>
<td>2217±85.2</td>
<td>1713±57.5†</td>
<td>1970±72.2†</td>
<td>2260±58.7</td>
</tr>
<tr>
<td>LV weight, mg</td>
<td>1000±45.2*</td>
<td>1614±65.5</td>
<td>1268±56.2†</td>
<td>1382±41.8†</td>
<td>1660±46.8</td>
</tr>
<tr>
<td>RV weight, mg</td>
<td>288±8.8*</td>
<td>364±12.0</td>
<td>327±13.9†</td>
<td>394±21.1</td>
<td>382±15.7</td>
</tr>
<tr>
<td>Left atria weight, mg</td>
<td>35.6±3.67*</td>
<td>45.1±2.27</td>
<td>44.1±4.37</td>
<td>47.1±4.04</td>
<td>56.5±6.61†</td>
</tr>
<tr>
<td>Lung weight, g</td>
<td>1.9±0.11</td>
<td>2.3±0.17</td>
<td>2.3±0.23</td>
<td>2.6±0.27</td>
<td>2.7±0.36</td>
</tr>
</tbody>
</table>

Values are mean±SEM. RV indicates right ventricle; NT, no treatment group.
*P<0.01 versus AR-NT group.
†P<0.05 versus AR-NT group.

Table 2. Data at Sacrifice (6 Months)

Table 3. Echocardiographic Data (6 Months)
and losartan decreased systolic blood pressure to a similar extent (mean of -12 mm Hg and -8 mm Hg, respectively). Nifedipine did not affect systolic blood pressure. Pulse pressure in the nifedipine group remained high and similar to untreated AR animals, whereas pulse pressure was the lowest in the captopril group. Losartan treatment decreased pulse pressure but to a lesser degree than captopril. Invasive intracardiac pressure measurements did not reveal any significant differences in dP/dt +, dP/dt −, or LV end-diastolic pressures between any of the AR groups (results not shown).

ANP and BNP mRNA Expression
The relative expression of ANP and BNP mRNA were measured after 6 months. Results are reported in Figure 1. All AR groups displayed a significant increase in ANP mRNA expression as shown in the top panel of Figure 1. Captopril (AR-C) treatment decreased this expression, whereas the other treatments had no significant impact. BNP expression was significantly increased in untreated AR rats. Both losartan (AR-L) and captopril (AR-C) prevented this increase in BNP mRNA expression. However, nifedipine (AR-N) had no impact and animals treated with this drug had similar BNP expression as the untreated AR animals.

ECM Remodeling-Related mRNA Expression
Results for the mRNA relative expression of collagen I, collagen III, and fibronectin are shown in Figure 2. Collagen I mRNA expression (top panel) was increased in untreated AR animals. Neither losartan nor nifedipine prevented this increase. Captopril strongly tended to normalize this parameter. Similar results were found for collagen III (middle panel). Captopril significantly prevented the increase of collagen III mRNA. Fibronectin expression increased in all AR groups regardless of treatment (bottom panel).

Pro-matrix metalloprotease 2 expression tended to increase in all AR groups but this trend did not reach statistical significance (Figure 3, top panel). Treatments did not affect this parameter. Tissue inhibitor of metalloprotease-1 expression tended to increase in the untreated AR group but significantly increased in all 3 treatment groups (Figure 3, middle panel). Losartan and captopril had a similar impact on tissue inhibitor of metalloprotease-1 expression, whereas the nifedipine group displayed the highest levels. LOX expression (lower panel) was increased in all AR groups but mostly in the losartan and nifedipine group. LOX expression was similar in the untreated AR group and the one treated with captopril.

The level of expression of TGFβ1, TGFβ2, and CTGF were also evaluated (Figure 4). The expression of TGFβ1 was increased in untreated AR animals (top panel). Only captopril could normalize this parameter. TGFβ2 expression was also increased in untreated AR (middle panel) and both losartan and captopril were able to decrease this overexpression.

Figure 1. Evaluation by real-time quantitative RT-polymerase chain reaction of the LV mRNA levels of the ANP and BNP after 6 months. Results are reported in arbitrary units as mean±SEM (n=9 to 11 per group). Sham group mRNA levels were normalized to 1. *P<0.05 and **P<0.01 versus AR-NT group.
Nifedipine was ineffective on that aspect. Results similar to those of TGFβ2 were found for CTGF expression (bottom panel).

**Discussion**

Vasodilators such as nifedipine and angiotensin I converting enzyme have been the cornerstone of the pharmacological therapy for AR volume overload for many years. Treatment of chronic volume overload remains, however, controversial and debated. The available evidence suggests that this type of treatment may have some favorable effects, but the limited evidence supporting or opposing the use of vasodilators in AR keeps us from drawing any firm conclusions. In our study, we compared 3 vasodilators in a reproducible rat model of AR which is free of confounding factors or coexisting comorbidities. We had previously reported that high doses of captopril were effective in rats with severe AR in both hypertensive and normotensive animals. In the current study, we conclude that nifedipine is not effective in our model as suggested by recent data in a human trial.
However, vasodilators targeting RAS definitively had some positive effects. Both losartan and captopril were able to slow LV hypertrophy and preserve LV ejection fraction. Both drugs effectively prevented the increase in cardiac output associated with volume overload. Captopril and Losartan also decreased systolic blood pressure as well as pulse pressure, whereas nifedipine was unable to affect this parameter despite a high dosage. BNP expression was almost normalized by captopril and losartan, whereas nifedipine had no effect at all on that parameter. Positive effects of the 2 RAS-targeting drugs were also found on the expression of fibrosis-related molecules such as collagens I and III, LOX, TGFβ1, TGFβ2, and CTGF. These findings suggest that RAS-targeting drugs have protective effects on the left ventricle submitted to chronic volume overload before the occurrence of systolic heart failure.

All 3 drugs were given at or even a higher dosage that was previously proven to have effective antihypertensive effects.14–16 It is interesting to note, however, that despite this high dose, nifedipine had no significant hemodynamic effect on the AR rats. On the opposite both captopril and losartan significantly reduced the cardiac output and decreased systolic pressure (similarly) and pulse pressure thereby decreasing the afterload. RAS inhibition therefore seems more effective to induce some hemodynamic benefits in our model of severe AR. It is also interesting to note that in the recent article by Evangelista et al3 in which nifedipine and enalapril were found to have no positive effect on LV remodeling, the investigators reported that neither treatments (nifedipine 40 mg/d or enalapril 20 mg/d) had any hemodynamic effects on systolic or diastolic blood pressure.

The absence of effect on pulse pressure of high doses of nifedipine may seem intriguing. Captopril and losartan significantly reduced systolic blood pressure (and consequently pulse pressure), whereas nifedipine had no effect. Increased pulse pressure (with mild systolic hypertension) in AR is mostly related to mechanical causes increasing afterload: an increased ejection volume in a large arterial bed of fixed compliance. It is interesting to note that nifedipine treatment was unable to reduce the ejection volume, whereas captopril and losartan had significant effects on that parameter. This lack of effect of nifedipine on the ejection volume may be one explanation for its lack of effect on systemic pressures. Secondly, part of the relative hypertension in our model may be due to an increase in adrenergic drive and RAS activation as we have previously reported. Considering that nifedipine has no direct effect on the RAS and may cause an adrenergic hyperactivation, it seems logical that it was less effective to normalize pulse pressure. However, this mechanism is probably less prominent in chronic AR because excessive small vessel vasoconstriction would have been expected to cause an increase (or at least stability) in diastolic BP, whereas there is a significant decrease in diastolic BP in AR animals. This finding favors the mechanical hypothesis. We have to remember that pure chronic AR is not a “hypertensive” state and that it may not respond to antihypertensive treatments as expected. Captopril and losartan were both effective in our study, whereas nifedipine was not. However, captopril and losartan did not yield totally similar results. They induced similar hemodynamic effects (comparable reduction in systolic blood pressure, normalization of stroke volume, and cardiac output) but despite these similarities, captopril-treated animals had a slightly lower LV mass, smaller left atria, right ventricles, and lungs as well as lower ANP expression. This suggests lower filling pressures in the captopril group. However, we were unable to detect any significant difference in LV end-diastolic pressures, dP/dt−,
or echographic diastolic parameters to correlate with this hypothesis. It is possible that our study was underpowered to detect any significant difference in those measurements. It is also important to note that all measurements were done under anesthesia in a fasting state and that this might have affected invasive measurements and blunted small differences.

The left ventricles of the captopril-treated animals also displayed less collagen I, collagen III, and LOX expression than the losartan group. These results suggest a less active ECM remodeling in the captopril group. Whether this would translate in added benefits versus treatment with losartan in the longer term remains to be established. Fibronectin mRNA expression on the other hand was not significantly modulated by either vasodilators used in this study. The accumulation of fibronectin in the left ventricle of AR models has been described in the past.\textsuperscript{6,17–19} We have previously shown that \( \beta \)-blockade could help normalize fibronectin expression. More importantly, we have previously reported that captopril can reduce the total LV fibronectin content in AR rats.\textsuperscript{6,19,20} The lack of effect of treatment on fibronectin mRNA expression in this protocol suggests that the turnover of fibronectin is still increased despite effective RAS blockade. Fibronectin has been shown to be regulated not only by RAS but also by stretch receptors. Considering that animals in the captopril and losartan groups had ejection volumes still \( >30\% \) higher than normal, similar end-diastolic diameters and similar LV end-diastolic pressures than nontreated AR animals, we can suppose that stretch receptors in the left ventricles were still significantly stimulated. Although collagen production by fibroblasts is also influenced by stretch receptors, it may be so in a lesser proportion.

In this study, we went a little further in describing the control of ECM remodeling. We observed the increase in mRNA levels encoding for the LOX enzyme, an important player in the cross-linking of collagen fibers.\textsuperscript{21} LOX has been shown to be upregulated in rat models of LV hypertrophy as well as in the heart of patients with congestive heart failure.\textsuperscript{22,23} Here, we observed that captopril was able to abolish the upregulation of LOX in the left ventricle of AR rats, which may help the left ventricle maintain a better diastolic function.\textsuperscript{24} This study also shows the implication of TGF\( \beta \) signaling in the LV ECM remodeling. Again, targeting the RAS helped normalize the gene expression upregulation of TGF\( \beta_1 \) and TGF\( \beta_2 \) as well as the one of CTGF. It is intriguing to observe this clear trend for enhanced collagen LV deposition, which is not clearly correlated with increased amounts of collagen fibers.\textsuperscript{17,19} We did observe increased perivascular collagen deposition in our rat AR model as well as increased general myocardial fibrosis after 1 year.\textsuperscript{10,25}

The differences between the captopril and losartan groups were not related to their hemodynamic effects because both drugs had similar impacts on hemodynamic parameters. Higher doses of losartan might have induced a more complete RAS blockade although the dose given to the animals in this protocol were already high and had measurable hemodynamic effects. It is known that RAS interacts with the sympathetic system at multiple levels and this interaction has been studied in heart failure models.\textsuperscript{26–28} We have previously reported that the sympathetic system is overactivated in our model of chronic AR before heart failure occurs and that blocking this adrenergic overactivation is beneficial.\textsuperscript{10,19} In a previous study by Balt et al.,\textsuperscript{29} captopril was shown to be more effective than losartan to inhibit angiotensin II-induced facilitation of the sympathetic system despite maximal dosage of both drugs. In our study, animals in the captopril and losartan group had similar resting heart rates (under anesthesia). However, we tested their heart rate response to a direct adrenergic stimulation (dobutamine infusion) and found that the heart rate increase was smaller in the captopril group compared with the losartan group (captopril: mean, \( +53 \) bpm; losartan: mean, \( +76 \) bpm), whereas both heart rate responses to dobutamine stimulation remained lower than the untreated AR group (mean, \( +94 \) bpm in untreated AR). RAS-targeting drugs (captopril more than losartan), therefore, seem to blunt the response to adrenergic stimulation in our model. The mechanisms of interaction between RAS and the adrenergic system in volume overload will be investigated more thoroughly in upcoming studies because the current protocol was not primarily designed to do so.

In conclusion, this study shows that captopril and losartan were effective to slow LV hypertrophy, remodeling, and loss of ejection fraction in a model of chronic severe AR before the occurrence of heart failure. Captopril seemed to confer some advantages over losartan. Nifedipine was totally ineffective in this animal model, correlating with the most recently reported data in humans. Animal models obviously have their pitfalls and one must remain very cautious before extrapolating these results to humans. A more thorough evaluation of the adrenergic status of the animals with chronic severe AR as well as the impact of combination therapy such as the coadministration of captopril with a \( \beta \)-blocker and/or losartan should be addressed in up-coming protocols and could yield important information. However, our findings suggest that nifedipine should probably be discarded and that high doses of RAS-targeting drugs deserve to be adequately retested in carefully designed human AR clinical trials.

**Acknowledgments**

Losartan was provided as an unrestricted gift from Merck-Frosst Canada.

**Sources of Funding**

This work was supported by operating grants to Drs Couet and Arsenaullt from the Canadian Institutes of Health Research (MOP-61818), the Heart and Stroke Foundation of Canada, and the Quebec Heart Institute Corporation.

**Disclosures**

Dr Plante and Mr Lachance received PhD studentships from the Canadian Institutes for Health Research; Drs Arsenaullt and Jacques Couet are senior scholars from the Fonds de la recherche en santé du Québec; and Drs Beaudoin and Champetier and Ms Roussel report no disclosures.

**References**


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**Clinical Perspective**

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Circ Heart Fail. 2009;2:25-32
doi: 10.1161/CIRCHEARTFAILURE.108.801548
Circulation: Heart Failure is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 1941-3289. Online ISSN: 1941-3297

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