Angiotensin Receptor Neprilysin Inhibitor LCZ696 Attenuates Cardiac Remodeling and Dysfunction After Myocardial Infarction by Reducing Cardiac Fibrosis and Hypertrophy

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Background—Angiotensin receptor neprilysin inhibitors (ARNi), beyond blocking angiotensin II signaling, augment natriuretic peptides by inhibiting their breakdown by neprilysin. The myocardial effects of ARNi have been little studied until recently. We hypothesized that LCZ696 attenuates left ventricular (LV) remodeling after experimental myocardial infarction (MI), and that this may be contributed to by inhibition of hypertrophy and fibrosis in cardiac cells.

Methods and Results—One week after MI, adult male Sprague–Dawley rats were randomized to treatment for 4 weeks with LCZ696 (68 mg/kg body weight perorally; MI-ARNi, n=11) or vehicle (MI-vehicle, n=6). Five weeks after MI, MI-ARNi versus MI-vehicle demonstrated lower LV end-diastolic diameter (by echocardiography; 9.7±0.2 versus 10.5±0.3 mm), higher LV ejection fraction (60±2 versus 47±5%), diastolic wall strain (0.23±0.02 versus 0.13±0.02), and circular strain (9.8±0.5 versus 7.3±0.5%; all \(P<0.05\)). LV pressure–volume loops confirmed improved LV function. Despite similar infarct size, MI-ARNi versus MI-vehicle had lower cardiac weights (\(P<0.01\)) and markedly reduced fibrosis in per-infarct and remote myocardium. Angiotensin II–stimulated incorporation of 3[H]leucine in cardiac myocytes and 3[H]proline in cardiac fibroblast was used to evaluate hypertrophy and fibrosis, respectively. The neprilysin inhibitor component of LCZ696, LBQ657, inhibited hypertrophy but not fibrosis. The angiotensin receptor blocker component of LCZ696, valsartan, inhibited both hypertrophy and fibrosis. Dual valsartan+LBQ augmented the inhibitory effects of valsartan and the highest doses completely abrogated angiotensin II–mediated effects.

Conclusions—LCZ696 attenuated cardiac remodeling and dysfunction after MI. This may be contributed to by superior inhibition of LCZ696 on cardiac fibrosis and cardiac hypertrophy than either stand-alone neprilysin inhibitor or angiotensin receptor blocker. (Circ Heart Fail. 2015;8:71-78. DOI: 10.1161/CIRCHEARTFAILURE.114.001785.)

Key Words: angiotensins ■ brain natriuretic peptide ■ cardiac hypertrophy ■ left ventricular remodeling ■ myocardial infarction

Hypertension and heart failure (HF) are major causes of death and morbidity in the Western world, and their prevalence is projected to increase.\(^1\)\(^-\)\(^3\) Increasing recognition that sustained overdrive of neurohormonal systems such as the renin–angiotensin–aldosterone system (RAAS) is involved in HF pathophysiology has led to the introduction of drugs inhibiting key components of the RAAS into clinical practice.\(^4\)\(^-\)\(^8\) The success of angiotensin-converting enzyme inhibitors and angiotensin receptor blockers (ARB) underscores the importance of RAAS as a target in these (and other) cardiovascular disorders.

In addition to the RAAS, counter-regulatory hormonal pathways are also activated in HF. The natriuretic peptide (NP) system counteracts the RAAS by promoting vasodilation, natriuresis, and inhibition of fibrosis and hypertrophy.\(^7\)\(^,\)\(^8\) Biologically active NPs are degraded by the enzyme neutral endopeptidase or neprilysin; consequently, neprilysin inhibition represents an important pharmacological approach to augment the salutary actions of NPs. Presumably because of its affinity toward multiple substrate peptides beyond the NPs such as endothelin-1 and angiotensin II, stand-alone neprilysin inhibitor (NEPi) has not been proven to be clinically efficacious.\(^9\)\(^,\)\(^10\) Simultaneous blockade of RAAS and neprilysin
through dual-acting ACE and NEPi (vasopeptidase inhibitors) has been evaluated a decade ago. Its prototypic drug, omapatrilat, showed favorable effects in clinical trials of hypertension and HF, but further development was halted because of increased rates of angioedema, presumably caused by accumulation of bradykinin in at-risk patients.13,14 Recently, a new drug class, angiotensin receptor neprilysin inhibitors (ARNi), have been developed to simultaneously block the RAAS and augment NPs through neprilysin inhibition at a presumed lower risk of bradykinin-induced angioedema.13,14 In a preclinical model, ARNi (using valsartan–candoxatril) provided similar antihypertensive efficacy as omapatrilat without inducing tracheal plasma extravasation (a surrogate of angioedema).15

LCZ696 has been the first ARNi to be evaluated in patients with hypertension and HF.16–18 LCZ696 combines a moiety of the ARB valsartan and the NEPi precursor, AHU377. After intake, LCZ696 is metabolized into active valsartan and inactive AHU377, whereas AHU377 is further cleaved into the active NEPi LBQ657. LCZ696 thus far has shown promising efficacy without significant occurrence of off-target effects. However, the effects of ARNi (LCZ696) on cardiac fibrosis, hypertrophy, and remodeling after myocardial infarction (MI) remain to be established.

We therefore hypothesized that LCZ696 would have beneficial effects on cardiac remodeling after experimental MI, and that this may be contributed to by inhibition of hypertrophy and fibrosis in cardiac cells.

Methods

Induction of MI, Treatment, and Study Protocol

Adult 6- to 8-week-old male Sprague–Dawley rats (220–250 g body weight) were subjected to induction of MI by left anterior descending ligature as routinely performed in our laboratory.19 Rats were randomized in a 2:1 fashion to 4 weeks of treatment with LCZ696 (68 mg/kg body weight perorally; MI-ARNi, n=11) or vehicle (MI-Vhc, n=6). LCZ696 was a kind gift of Novartis, Basel, Switzerland. Treatment commenced 1 week after surgery (baseline) to avoid interference with the measurements, tissues were harvested and fixed in neutral buffered formalin and processed for histopathology.

The investigation conformed with the Guide for the Care and Use of Laboratory Animals published by the US National Institutes of Health (PHS Approved Animal Welfare Assurance No. A5587-01). All animal usage was also approved by St. Vincent’s Hospital’s Animal Ethics Committee in accordance with National Health and Medical Research Council’s Guide for the Care and Use of Laboratory Animals (Animal Ethics Committee No. 028/11).

Histological Analysis of Cardiac Tissue

Paraffin-embedded LV tissue sections (4 μm) were stained with picrosirius red to determine interstitial fibrosis using Aperio ScanScope Consol v.8.0.0.1058 (AperioTechnologies, Inc). Picrosirius red staining in the noninfarct zone and peri-infarct zone of the LV was selected for its intensity of staining, and the percentage area was calculated using an established algorithm.19 Similarly, perivascular fibrosis was defined as the area of picrosirius red staining immediately surrounding the adventitia of the intramural coronary arteries. The intensity and algorithm were preset and maintained constant for analysis of all sections. Infarct size was expressed as an averaged percentage of the endocardial and epicardial scarred circumferences of the LV.

Cellular Cardiac Hypertrophy and Fibrosis In Vitro

Rat neonatal cardiac myocytes and fibroblasts were obtained from 1- to 2-day-old Sprague–Dawley rat pups by enzymatic collagenase digestion and prepared for in vitro assays as routinely used in our laboratory.20 Cardiac myocyte hypertrophy was assessed by AngII-stimulated (100 nmol/L) neonatal cardiac myocytes with 3[H]leucine incorporation for 60 hours. AngII-stimulated (100 nmol/L) collagen synthesis was determined by 3[H]proline incorporation in neonatal cardiac fibroblasts for 48 hours. Cells were preincubated with valsartan, AHU377, LBQ657, or valsartan+LBQ657 (ARNi) for 1 hour before stimulation. Dose ranges used and NEPi to ARB ratios aimed to replicate as far as possible doses of LCZ696 used clinically. The drugs were a kind gift of Novartis, Basel, Switzerland. In addition, exogenous B-type natriuretic peptide (BNP) was added at different concentrations into the cell culture media just before AngII stimulation to assess the effect of direct augmentation of NP signaling. Experiments were repeated 2 to 4x in triplicate each time.

Echocardiography and Hemodynamic Measurements

Standard 2-dimensional and Doppler echocardiography was performed before and after 4 weeks of treatment in lightly anesthetized animals (40 mg/kg ketamine and 5 mg/kg IP xylazine) using a commercially available system (GE Vingmed Vivid 7, Horten, Norway) with a 10-MHz phased array probe, as routinely used in our laboratory.19 All recordings were analyzed off-line by an experienced specialist using commercially available customized software within a personal computer workstation (EchoPac vers108.1.0, GE Vingmed, Horten, Norway). LV basal rotation and systolic circular LV strain were determined by speckle tracking analysis of LV basal short axis views.21 Diastolic wall strain, an index of diastolic stiffness based on the linear elastic theory, was defined as the difference between systolic and diastolic posterior wall thickness divided by systolic posterior wall thickness.22 Animals were anesthetized with pentobarbitone (60 mg/kg IP) and intubated for cardiac catheterization procedures, as previously described.19 Briefly, animals were ventilated and a 2-F miniaturized combined catheter/micromanometer (model SPR838; Millar Instruments, Houston, TX) was inserted into the right common carotid artery to obtain aortic blood pressure and then advanced into the left ventricle to obtain LV pressure–volume loops. Pressure–volume loops were recorded at steady state and during transient preload reduction, achieved by occlusion of the inferior vena cava and portal vein with the ventilator turned off and animal apnoeic. The following validated parameters were assessed using Millar conductance data acquisition and analysis software PVAN 3.5: LV end-systolic pressure, LV end-diastolic pressure, maximal and minimal change in pressure over time (dP/dt max and dP/dt min), τ (t Logistic), and the slope of the preload recruitable stroke work relationship. At the conclusion of the measurements, tissues were harvested and fixed in neutral buffered formalin and processed for histopathology.

Statistical Analysis

Values are expressed as mean±SEM. For in vivo experiments, unpaired Student t test was used. For cell studies, 1-way ANOVA with Bonferroni post hoc analysis was used for comparison among all groups and paired t test was used for comparisons between treated groups using GraphPad Prism software version 5 as described.22 A 2-tailed P value of <0.05 was considered significant.

Results

Effects of ARNi on Cardiac Hypertrophy and Fibrosis After Experimental MI

After 4 weeks of treatment, MI-ARNi exhibited significantly smaller weights compared with MI-Vhc in all cardiac chambers,
consistent with reduced cardiac hypertrophy (Table 1). Lung and kidney weights were similar between groups. Although heart rate was comparable, blood pressure trended to be lower with LCZ696 versus MI-Vhc. The degree of fibrosis both in noninfarcted remote myocardium (Figure 1A) and in the peri-infarct zone (Figure 1B) was significantly reduced in MI-ARNi versus MI-Vhc. In contrast, no differences in perivascular fibrosis in noninfarcted (Figure 1C) or peri-infarct (Figure 1D) myocardium were discerned.

Effects of ARNi on LV Remodeling and Function
Infarct size was substantial and consistent with large MI, and similar in both groups (Figure 1E). Echocardiography 1 week after MI before treatment demonstrated similar LV dimensions and function in both groups (Table 2).

At end point, MI-ARNi exhibited smaller LV cavity dimensions with unaltered wall thickness versus MI-Vhc (Table 3). Computed LV mass with MI-ARNi was lower than MI-Vhc, consistent with organ weights. Ejection fraction and fractional area change were increased, as was diastolic wall strain.

Doppler echocardiography analysis revealed similar early and reduced late diastolic filling and a trend toward higher E/A ratios in MI-ARNi versus MI-Vhc. This was reflected by a similar pattern of early and late myocardial velocities by TDI. E/é ratios (an estimate of LV filling pressure) and systolic myocardial velocities were similar between groups. At similar degree of basal rotation, circular strain was increased in MI-ARNi versus MI-Vhc.

Hemodynamics in ARNI- Versus Vehicle-Treated Rats After MI
Analysis of steady-state LV pressure–volume loops in vivo revealed no statistically significant differences in heart rate, LV volumes, LV pressures, cardiac output, or arterial pressures (Table 1). However, LV unloading by caval vein occlusion revealed a significantly higher end-systolic pressure–volume relationship (P<0.001), lower τ (P<0.05), and a trend for lower end-diastolic pressure–volume relationship (P=0.10) in MI-ARNi versus MI-Vhc animals.

Renal Function After MI
Renal function in MI-Vhc and MI-ARNi at baseline was similar, and neither urinary creatinine nor proteinuria changed significantly in either group. Despite small increases in plasma creatinine in both groups during the study period, the difference between values at end point versus baseline was significant only in MI-Vhc (not shown). GFR significantly decreased in both groups to a greater extent in MI-Vhc; accordingly, both absolute GFR values at end point (MI-Vhc 7.1±0.5 versus MI-ARNi 8.3±0.3 mL/min per kilogram; P=0.07) and the difference in changes in GFR over time (MI-Vhc –4.7±0.7 versus MI-ARNi –3.6±0.2 mL/min per kilogram; P=0.09) nearly reached significance.

Effects of Stand-Alone NEPi on Cellular Cardiac Fibrosis and Hypertrophy
AngII induced profound collagen accumulation in fibroblasts (Figure 2A) and cardiac myocyte hypertrophy (Figure 2B), respectively, as has been shown previously.22 The inactive NEPi precursor, AHU377, did not inhibit collagen accumulation in fibroblasts nor cardiac myocyte hypertrophy (data not shown). In cardiac fibroblasts, the active NEPi LBQ657 had no discernible effects (Figure 2A). In contrast, LBQ657 modestly inhibited cardiac myocyte hypertrophy (Figure 2B).

Effects of Stand-Alone ARB and ARNi on Cardiac Fibrosis and Hypertrophy
Valsartan dose dependently inhibited collagen accumulation in fibroblasts (Figure 3A) and cardiac myocyte hypertrophy (Figure 3B), respectively. In cardiac fibroblasts, addition of LBQ657 (10 μmol/L) significantly augmented the inhibitory effects of valsartan except for the highest dose where both valsartan and velsartan+LBQ657 values were reduced to unstimulated negative control values (Figure 4A). In cardiac myocytes, addition of LBQ657 (10 μmol/L) significantly augmented the inhibitory effects of the lowest dose of valsartan; however, only the highest combined dose of ARNi (valsartan+LBQ657) afforded complete inhibition of AngII-induced hypertrophy to values that were similar to unstimulated negative controls (Figure 4B).

BNP Reduced AngII-Stimulated Cellular Cardiac Hypertrophy and Cardiac Fibrosis
Increasing doses of BNP into culture media dose dependently reduced AngII-stimulated collagen synthesis in cardiac

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**Table 1.** Hemodynamics and Organ Weights in MI Rats After 4 Weeks of Treatment With Vhc or LCZ696 (ARNi)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MI-Vhc (n=6)</th>
<th>MI-ARNi (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hemodynamics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Systolic blood pressure, mm Hg</td>
<td>117±8</td>
<td>100±6</td>
</tr>
<tr>
<td>Heart rate, beats per minute</td>
<td>266±11</td>
<td>254±10</td>
</tr>
<tr>
<td>Cardiac output, mL/min</td>
<td>59.5±4.5</td>
<td>64.4±7.1</td>
</tr>
<tr>
<td>PRSW</td>
<td>65.3±11.2</td>
<td>80.3±8.2</td>
</tr>
<tr>
<td>LVdp</td>
<td>9.9±3.5</td>
<td>6.4±0.8</td>
</tr>
<tr>
<td>dp/dt max</td>
<td>5036±368</td>
<td>5204±482</td>
</tr>
<tr>
<td>dp/dt min</td>
<td>–4446±439</td>
<td>–4289±350</td>
</tr>
<tr>
<td>τ</td>
<td>12.0±1.7</td>
<td>8.9±0.38*</td>
</tr>
<tr>
<td>Ea</td>
<td>0.48±0.46</td>
<td>0.16±0.11</td>
</tr>
<tr>
<td>EDpvr</td>
<td>0.032±0.007</td>
<td>0.019±0.004</td>
</tr>
<tr>
<td>ESPvr</td>
<td>0.27±0.04</td>
<td>0.46±0.02†</td>
</tr>
<tr>
<td><strong>Body and organ weights</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body weight, g</td>
<td>385±5</td>
<td>380±7</td>
</tr>
<tr>
<td>LV weight, mg</td>
<td>887±20</td>
<td>803±25*</td>
</tr>
<tr>
<td>RV weight, mg</td>
<td>272±11</td>
<td>241±8*</td>
</tr>
<tr>
<td>Atrial weight, mg</td>
<td>160±12</td>
<td>125±8*</td>
</tr>
<tr>
<td>Total heart weight, mg</td>
<td>1319±21</td>
<td>1168±35†</td>
</tr>
<tr>
<td>Lung weight, mg</td>
<td>1552±44</td>
<td>1544±56</td>
</tr>
<tr>
<td>Kidney weight, mg</td>
<td>2615±76</td>
<td>2667±119</td>
</tr>
</tbody>
</table>

ARNi indicates angiotensin receptor neprilysin inhibitor; dp/dt max, maximum pressure decay; dp/dt min, minimum pressure decay; Ea, arterial elastance; EDpvr, end-diastolic pressure–volume relationship; ESPvr, end-systolic pressure–volume relationship; LVdp, left ventricular end-diastolic pressure; LV, left ventricular; MI, myocardial infarction; PRSW, preload-recruitable stroke work; RV, right ventricular; and Vhc, vehicle.

*P<0.05; †P<0.01; MI-ARNi vs MI-Vhc; unpaired t test.
fibroblasts (Figure 5A) as well as cardiac myocyte hypertrophy (Figure 5B). The highest BNP dose (ie, 10^{-8} \text{ mol/L}) resulted in inhibition at levels that were not different from unstimulated negative controls.

**Discussion**

We herein present novel data on the effects of LCZ696, a first-in-class ARNi, on post-MI cardiac remodeling and on AngII-induced hypertrophy and fibrosis in cardiac cell lines.

First, our data show that treatment with LCZ696 versus vehicle resulted in attenuation of cardiac dysfunction, fibrosis and remodeling, and somewhat attenuated decline in kidney function in rats after experimental MI. Second, although the inactive NEPi precursor, AHU377, did not affect AngII-stimulated cellular cardiac hypertrophy and fibrosis, its active metabolite LBQ657 in vitro modestly inhibited cardiac hypertrophy, but not cardiac fibrosis. Third, valsartan potently inhibited AngII-stimulated cellular cardiac hypertrophy and cardiac fibrosis. Fourth, concomitant LBQ657 and valsartan augmented the effects of the stand-alone ARB valsartan in cell culture. Finally, BNP dose dependently inhibited AngII-mediated effects in both cell types, providing further rationale for augmentation of salutary NP effects in cardiac hypertrophy and fibrosis.

Cardiac dysfunction and remodeling were attenuated by 4 weeks treatment with LCZ696, commencing 1 week after experimental MI. The delay in commencement of treatment aimed to avoid interference with reparative scar tissue formation and hemodynamic stabilization. Despite large and similar infarct size in both groups, organ weights and cardiac dimensions (by echocardiography) consistently showed a 15% to 20% reduction in LV size by LCZ696. Moreover, echocardiography and in vivo hemodynamic measurements revealed better preservation of cardiac function. Although early diastolic LV inflow and myocardial velocities were not different, lower late diastolic LV inflow, reduced diastolic wall strain (ie, an index of LV diastolic stiffness), lower \( \tau \), higher end-diastolic pressure–volume relationship, and reduced atrial size all support better-preserved diastolic function. This is consistent with effects of LCZ696 to reduce atrial adverse remodeling in patients with heart failure with preserved ejection fraction even in the absence of discernible effects on LV diastolic filling.\(^{17}\) Here, MI rats did not exhibit signs of overt HF, for example, elevated lung weights but it may be reasonable to assume that HF would have developed during longer observation time, although the study was not designed to assess evolution to HF or mortality. The observed improvements in cardiac function afforded by LCZ696 may be related both to reduced cardiac hypertrophy (as manifest by decreased LV weight and mass) and a reduction in interstitial fibrosis in the peri-infarct and remote myocardium, but not perivascular fibrosis. Further mechanistic studies are required to elucidate the precise effect on profibrotic signaling cascades.

A previous report investigating dual pathway inhibition with omapatrilat versus the ARB candesartan demonstrated that both agents attenuated LV remodeling and dysfunction as well as several profibrotic peptides in rats after ischemia–reperfusion injury.\(^{23}\) In addition, Bäcklund et al\(^{24}\) showed superior efficacy of omapatrilat versus captopril on

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**Figure 1.** Effects of chronic administration of LCZ696 on cardiac fibrosis after myocardial infarction (MI). Paraffin-embedded left ventricular (LV) tissue sections stained with picrosirius red revealed markedly and significantly reduced interstitial fibrosis with LCZ696 (MI-angiotensin receptor neprilysin inhibitor [ARNi]) both in the noninfarct zone (A) and in the peri-infarct zone (B) compared with MI-vehicle (Vhc). In contrast, perivascular fibrosis was not different between groups in noninfarct zone (C) and peri-infarct zone (D). Infarct size as expressed as an averaged percentage of the endocardial and epicardial scarred circumferences of the left ventricular was substantial and similar in both groups (E). *P<0.05; **P<0.01; MI-ARNi vs MI-Vhc.
cardiomyocyte apoptosis and cardiac remodeling after MI. LCZ696 also seems to show similar increased efficacy beyond stand-alone RAAS blockade as omapatrilat in this study. The clinical introduction of omapatrilat had been halted because of increased rates of angioedema in clinical trials leading to the development of ARNi.

Our in vitro studies were designed to test whether effects of LCZ696 on LV remodeling were contributed to by direct actions on relevant cardiac cell types. Furthermore, we were specifically interested in whether NEPi resulted in incremental effects on cardiac fibrosis as well as hypertrophy, in addition to that achieved by ARB. Our data did not demonstrate an in vitro effect of the inactive NEPi prodrug AHU377 in either cell type. This is consistent with the established mode of action of AHU377 requiring enzymatic cleavage to LBQ657, the active inhibitor of neprilysin. LBQ657, however, showed a distinct pattern of action in the different cell types. In cardiac fibroblasts, no discernible effect of LBQ657 at any tested dose was found despite clear add-on effects (when added to valsartan) and despite similar efficacy of exogenous BNP to inhibit AngII-mediated signaling in that cell type. Although not specifically tested, increase in other, potentially unfavorable neprilysin substrates such as endothelin or even AngII itself may have counteracted NEPi-induced augmentation of BNP, resulting in neutral effects on collagen accumulation. This is consistent with neutral net effects of NEPi in humans.9,10,25 In contrast, stand-alone LBQ657 was found to attenuate hypertrophy in cardiac myocytes.

Predictably, valsartan potently attenuated AngII-induced signaling in both cell types. Addition of LBQ657 to valsartan (replicating an ARNi) further augmented inhibitory effects. This was also observed in cardiac fibroblasts in which stand-alone LBQ657 did not produce discernible effects despite cardiac fibroblasts having been shown to produce BNP in response to various noxious stimuli.26 In contrast, stand-alone LBQ657 was found to attenuate hypertrophy in cardiac myocytes. AngII-mediated signaling in that cell type. Although not specifically tested, increase in other, potentially unfavorable neprilysin substrates such as endothelin or even AngII itself may have counteracted NEPi-induced augmentation of BNP, resulting in neutral effects on collagen accumulation. This is consistent with neutral net effects of NEPi in humans.9,10,25 Table 2. Baseline Echocardiography in Rats 1 Week After MI Before Treatment With Vhc or ARNi

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MI-Vhc (n=6)</th>
<th>MI-ARNi (n=110)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV end-diastolic diameter, mm</td>
<td>8.1±0.1</td>
<td>7.7±0.4</td>
</tr>
<tr>
<td>LV end-systolic diameter, mm</td>
<td>5.6±0.4</td>
<td>6.2±0.2</td>
</tr>
<tr>
<td>Anterior wall thickness, mm</td>
<td>1.29±0.01</td>
<td>1.40±0.05</td>
</tr>
<tr>
<td>Diastolic wall strain</td>
<td>0.15±0.02</td>
<td>0.16±0.02</td>
</tr>
<tr>
<td>LV ejection fraction, %</td>
<td>57.3±0.1</td>
<td>51±1</td>
</tr>
<tr>
<td>E/A</td>
<td>1.84±0.24</td>
<td>1.98±0.21</td>
</tr>
<tr>
<td>E/E₀</td>
<td>20.8±2.1</td>
<td>23.8±2.0</td>
</tr>
</tbody>
</table>

No significant differences, MI-ARNi vs MI-Vhc; unpaired t test. ARNi indicates angiotensin receptor neprilysin inhibitor; LV, left ventricular; MI, myocardial infarction; and Vhc, vehicle.

Table 3. Left Ventricular Function by Echocardiography in MI Rats After 4 Weeks of Treatment With Vhc or ARNi

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MI-Vhc (n=5)</th>
<th>MI-ARNi (n=11)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LV end-diastolic diameter, mm</td>
<td>10.5±0.3</td>
<td>9.7±0.2*</td>
</tr>
<tr>
<td>LV end-systolic diameter, mm</td>
<td>8.4±0.7</td>
<td>7.6±0.2</td>
</tr>
<tr>
<td>Anterior wall thickness, mm</td>
<td>1.12±0.06</td>
<td>1.09±0.02</td>
</tr>
<tr>
<td>Diastolic wall strain</td>
<td>0.13±0.03</td>
<td>0.23±0.02†</td>
</tr>
<tr>
<td>LV end-diastolic volume, mL</td>
<td>0.55±0.03</td>
<td>0.50±0.03</td>
</tr>
<tr>
<td>LV end-systolic volume, mL</td>
<td>0.30±0.03</td>
<td>0.20±0.03*</td>
</tr>
<tr>
<td>LV ejection fraction, %</td>
<td>47±5</td>
<td>60±2*</td>
</tr>
<tr>
<td>Computed LV mass, mg</td>
<td>959±68</td>
<td>793±32*</td>
</tr>
<tr>
<td>E, m/s</td>
<td>0.79±0.04</td>
<td>0.69±0.03</td>
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<tr>
<td>A, m/s</td>
<td>0.55±0.05</td>
<td>0.41±0.02*</td>
</tr>
<tr>
<td>E/A</td>
<td>1.46±0.10</td>
<td>1.72±0.11</td>
</tr>
<tr>
<td>E/E₀</td>
<td>21.1±1.1</td>
<td>20.0±1.8</td>
</tr>
<tr>
<td>E/E₀ /A</td>
<td>1.14±0.17</td>
<td>1.46±0.16</td>
</tr>
<tr>
<td>Circular strain, %</td>
<td>−7.3±0.5</td>
<td>−9.8±0.5†</td>
</tr>
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</table>

*P<0.05; and †P<0.01; MI-ARNi vs MI-Vhc; unpaired t test. ARNi indicates angiotensin receptor neprilysin inhibitor; LV, left ventricular; MI, myocardial infarction; and Vhc, vehicle.

Figure 2. Effects of LBQ657 in cardiac fibroblasts and myocytes. A, Effects of stand-alone neprilysin inhibitor (NEPi) LBQ657 on cardiac fibrosis and hypertrophy in vitro. Similar to the inactive NEPi prodrug AHU377, the active NEPi LBQ657 did not show discernible effects on angiotensin (Ang) II–induced collagen accumulation in cardiac fibroblasts (A). In contrast, LBQ657 modestly attenuated AngII-induced cardiac myocyte hypertrophy although without a clear dose-response (B). **P<0.0001, AngII vs control; #P<0.05; ##P<0.01; ####P<0.0001, LBQ657 vs AngII.

In patients with HF, elevated NP levels are frequently found in concert with the degree of cardiac dysfunction and...
Despite their natriuretic and diuretic effects, administration of synthetic NPs has failed to improve clinical outcomes, at least in the acute setting. Conceptually ARNi offers the advantage of augmenting endogenous NPs, combining their benefits with those of ARBs, well-established drugs in hypertension and HF. Contemporary clinical data underscore the efficacy of ARNi in patients with hypertension and heart failure with preserved ejection fraction consistent with leveling off of valsartan efficacy at either cell type. Even at the highest valsartan concentration a small but significant residual AngII-stimulated effect still could be observed. ****P<0.0001, AngII vs control; ###P<0.001, ####P<0.0001, valsartan vs AngII.

Figure 3. Effects of single angiotensin receptor blocker, valsartan on cellular cardiac fibrosis and hypertrophy. As expected, angiotensin (Ang) II–stimulated collagen synthesis in cardiac fibroblasts (A) and cardiac myocyte hypertrophy (B), respectively, were robustly and dose dependently inhibited by angiotensin receptor blockade with valsartan. Yet, the degree of inhibition did not increase much further from the second highest to highest valsartan concentration consistent with leveling off of valsartan efficacy at either cell type. Even at the highest valsartan concentration a small but significant residual AngII-stimulated effect still could be observed. ****P<0.0001, AngII vs control; ###P<0.001, ####P<0.0001, valsartan vs AngII.

Figure 4. Effects of angiotensin receptor nephrilysin inhibitor (ARNi) compared with stand-alone angiotensin receptor blocker (ARB) on cellular cardiac fibrosis and hypertrophy. Although inefficient as stand-alone, addition of fixed-dose LBQ657 (10 μmol/L) significantly augmented the inhibitory effects of valsartan (VAL) in cardiac fibroblasts. This was true for all VAL doses except for the highest dose where the difference between ARB (VAL) and ARNi (VAL+LBQ657) values were smaller than their differences with unstimulated negative control values (A). Accordingly, ARNi with both the second highest and the highest VAL concentration abrogated AngII signaling completely. In cardiac myocytes, addition of fixed-dose LBQ657 (10 μmol/L) significantly augmented the inhibitory effects of the lowest, but not the 2 middle-range VAL doses. Only the highest combined dose of ARNi (VAL+LBQ) afforded complete inhibition of AngII-induced hypertrophy to values not different from unstimulated negative controls (B). ****P<0.0001, AngII vs control; ###P<0.001, ####P<0.0001, LBQ657 vs AngII; $P<0.05, VAL vs LBQ+VAL.

Limitations

This study used only male rats, thus sex differences in efficacy, if any, cannot be determined from this work. The PARADIGM-HF trial did not show heterogeneity in efficacy response across sexes.

The use of sedation and anesthesia for echocardiography and invasive hemodynamic assessment, respectively, may have influenced the results. However, we used a consistent level of anesthesia across all animals reflected by similar symptom status. Despite their natriuretic and diuretic effects, administration of synthetic NPs has failed to improve clinical outcomes, at least in the acute setting. Conceptually ARNi offers the advantage of augmenting endogenous NPs, combining their benefits with those of ARBs, well-established drugs in hypertension and HF. Contemporary clinical data underscore the efficacy of ARNi in patients with hypertension and heart failure with preserved ejection fraction to alter blood pressure and important surrogate end points, with an acceptable safety profile.16,17,27 Recently, the prospective comparison of ARNi with angiotensin-converting enzyme inhibitors to Determine Impact on Global Mortality and morbidity in Heart Failure trial (PARADIGM-HF), a large (n=8422) outcome study assessing efficacy and safety of LCZ696 versus the angiotensin-converting enzyme inhibitors, enalapril, in patients with HF and reduced ejection fraction was stopped prematurely after interim analysis suggested superiority over standard therapy with angiotensin-converting enzyme inhibitors, the current gold standard.18,28 PARADIGM-HF will likely provide definite answers on the efficacy and safety of LCZ696 in HF. Given that many patients in PARADIGM-HF have an ischemic basis to their LV dysfunction, the findings of the present study will likely provide mechanistic insight into the benefits of LCZ696 in PARADIGM.29
The highest BNP dose (ie, 10−8 mol/L) resulted in inhibition at 0.05, **P<0.01, and ***P<0.001.

Effects of exogenous B-type natriuretic peptide (BNP) on angiotensin (Ang) II–stimulated cellular cardiac hypertrophy and fibrosis in vitro. Coincubation with increasing doses of BNP in cell culture media dose dependently reduced AngII-stimulated collagen accumulation in cardiac fibroblasts (A) and hypertrophy of cardiac myocytes (B). No further inhibition was observed between 10−9 and 10−8 mol/L consistent with plateau of response. The highest BNP dose (ie, 10−8 mol/L) resulted in inhibition at levels that were not different from unstimulated negative controls. *P<0.05, **P<0.01, and ***P<0.001, BNP (logM) vs AngII.

In summary, we have shown that the ARNi LCZ696 attenuated cardiac remodeling and dysfunction after experimental MI and inhibited cardiac fibrosis and cardiac hypertrophy in vivo after MI, as well as in vitro beyond that achieved by stand-alone ARB. Our data may offer novel mechanistic insight into the benefits observed with LCZ696 in clinical studies. The present findings suggest that LCZ696, by combining RAAS blockade with augmentation of beneficial NP effects, has potential as a novel therapeutic agent after MI as well as in a broader spectrum of cardiovascular disorders.

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Disclosures

Dr Krum has research contracts and has served as a consultant to Novartis. Dr von Lueder has received lecture honoraria from Novartis. The other authors report no conflicts.

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**CLINICAL PERSPECTIVE**

Natriuretic peptides, among the most potent endogenous vasodilators in man, are activated on increased cardiac stress occurring in heart failure and other cardiovascular diseases. Natriuretic peptides exert their actions on the kidneys and protect the heart and vasculature through volume and pressure unloading. This mechanism seems to become deficient in heart failure at least in part by increased activity of neprilysin, the endopeptidase that breaks down natriuretic peptides (and angiotensin II). Recently, the first-in-class angiotensin receptor neprilysin inhibitor (ARNI) LCZ696 showed efficacy in a phase II study in patients with heart failure (PARAMOUNT [Prospective comparison of ARNI with ARB on Management Of heart failureUre with preserved ejection fraction]) and preserved ejection fraction as well as in those with reduced ejection fraction (PARADIGM-HF [Prospective comparison of ARNI with angiotensin-converting enzyme inhibitors to Determine Impact on Global Mortality and morbidity in Heart Failure trial]). The present study evaluated effects of ARNI on cardiac remodeling after myocardial infarction, as well as potential direct effects on cardiac hypertrophy and fibrosis. Our data demonstrate a significant reduction in post–myocardial infarction cardiac remodeling and dysfunction, accompanied by a marked reduction in pathological fibrosis. In addition, ARNI exhibited potent antifibrotic and antihypertrophic effects in cardiac cells beyond either single neprilysin inhibition or stand-alone angiotensin receptor blocker. This is suggestive of synergistic effects of dual blockade of these 2 key therapeutic targets. B-type natriuretic peptide replicated the actions of ARNI on angiotensin II–stimulated cardiac cells, suggesting, additional to hemodynamic unloading, that direct cardioprotective effects of natriuretic peptides are exerted in conditions of neurohormonal activation. Our data therefore provide novel mechanistic insight into efficacy of ARNI in recent clinical trials and suggest evaluation in a broader setting of cardiovascular disease associated with fibrosis and hypertrophy such as post–myocardial infarction and in cardiorenal syndrome.
Angiotensin Receptor Neprilysin Inhibitor LCZ696 Attenuates Cardiac Remodeling and Dysfunction After Myocardial Infarction by Reducing Cardiac Fibrosis and Hypertrophy

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Supplemental figure: Changes in key echocardiography parameters shown as differences (deltas) in values at final minus at baseline assessment. Changes in LV end-diastolic volume were not statistically different between groups (A). Compared to MI-Vhc, MI-ARNi showed significant differences of changes in LV end-systolic volumes (B), ejection fraction (C), and computed LV mass (D) consistent with attenuation of adverse LV remodelling and dysfunction. While the difference in changes in diastolic wall strain (E) did not reach statistical significance, changes in LV fractional area change did (F). **p<0.01, MI-ARNi vs MI-Vhc, unpaired t-test; ns, no significant differences.
Clinical Perspective

Clinical experience with phosphodiesterase 3 inhibitors (PDE3i) in pediatric patients with idiopathic cardiomyopathy (IDC) demonstrates improved heart failure symptoms without the increased incidence of sudden death seen in adults treated with PDE3i. Elevated cAMP and higher downstream phospholamban phosphorylation may contribute to sustained hemodynamic benefits in pediatric IDC patients treated with PDE3i. In contrast, higher total PDE and PDE3 activities in adult IDC patients treated with PDE3i may perpetuate lower myocardial cAMP levels, limiting potential benefits of PDE3i therapy. This study represents the first investigation of the chronic myocardial effects of PDE3i treatment in both children and adults with IDC. The described differences in myocardial response to chronic PDE3i treatment between children and adults with IDC are part of a growing body of literature demonstrating that pediatric myocardial adaptation is unique and could have implications for future clinical treatment paradigms.

LCZ696 is a dual angiotensin receptor neprilysin inhibitor (ARNI) approved for the treatment of heart failure with reduced ejection fraction (HFrEF) in adults. Its effects on myocardial remodeling and fibrosis in pediatric patients with idiopathic cardiomyopathy (IDC) treated with LCZ696 have not been extensively studied. This study aimed to evaluate the chronic myocardial effects of LCZ696 treatment in children with IDC, comparing it to adults treated with the same agent.

Ongoing studies using LCZ696 in pediatric patients with IDC suggest that the drug may provide superior myocardial protection compared to adults, leading to improved heart failure symptoms and reduced rates of sudden death. Further research is needed to fully understand the unique effects of LCZ696 in pediatric myocardial adaptation and to develop individualized treatment strategies for this patient population.