Tolvaptan Improves Left Ventricular Dysfunction after Myocardial Infarction in Rats

Yamazaki et al: Role of Tolvaptan in Left Ventricular Dysfunction

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DOI: 10.1161/CIRCHEARTFAILURE.112.968750

Journal Subject Codes: [11] [118] [130]
Abstract

Background—Arginine vasopressin (AVP), which promotes the reabsorption of renal water is increased in chronic heart failure. Here, we compared the effects of tolvaptan, a newly developed non-peptide V$_2$ receptor antagonist, with those of furosemide, a loop diuretic, and a combination of these 2 agents in rats with left ventricular (LV) dysfunction after myocardial infarction (MI).

Methods and Results—After 10 week of MI induction, rats were separated them into the following 6 groups adjusted to the infarct size: a vehicle group, a group treated with 15 mg·kg$^{-1}$·day$^{-1}$ of furosemide; 2 groups treated with 3 or 10 mg·kg$^{-1}$·day$^{-1}$ of tolvaptan, and 2 groups treated with 15 mg·kg$^{-1}$·day$^{-1}$ of furosemide plus 3 or 10 mg·kg$^{-1}$·day$^{-1}$ tolvaptan. Each treatment agent was administered for 4 weeks, and all groups had similar blood pressure levels and infarct size. The tolvaptan-treated groups were found to have lower levels of LV end-diastolic and systolic cardiac volumes than the vehicle group. Furthermore, the improvement in the ejection fraction in the tolvaptan-treated groups was significantly greater than those in the vehicle group. ED-1 immunostaining and Sirius red staining revealed that tolvaptan significantly repressed MI-induced macrophage infiltration and interstitial fibrosis in the left ventricle, respectively. Tolvaptan attenuated the MI-induced mRNA expressions of atrial and brain natriuretic peptides, monocyte chemotactic protein-1, transforming growth factor-β1, AVP V$_{1a}$ receptor, and endothelin-1 in the marginal infarct region.

Conclusions—Tolvaptan may improve cardiac dysfunction after MI, which is partially mediated by the suppression of V$_{1a}$ receptor, neurohumoral activation and inflammation.

Key Words: arginine vasopressin, diuretic, echocardiography, left ventricular dysfunction, tolvaptan
Chronic heart failure (HF) is a clinical syndrome characterized by decreases in cardiac function, exercise tolerance, and quality of life; it has been associated with high morbidity and mortality. Although angiotensin-converting enzyme inhibitors, angiotensin receptor II blockers, beta-blockers, and anti-aldosterone drugs have improved cardiac remodeling and function, therapeutic agents available for chronic HF, especially refractory HF, are still not optimal. Chronic HF patients may have body fluid retention owing to the development of ischemic or valvular heart disease, excessive fluid intake, or stress of infection and can, therefore, present with symptoms of congestive HF. In order to prevent the occurrence of congestive HF, diuretics are used to regulate the body fluid volume. Several classes of diuretics are available for the treatment of congestive HF; these include loop diuretics, thiazide diuretics, potassium-sparing diuretics (anti-aldosterone drugs), and carbonic anhydrase inhibitors. However, in some cases of chronic HF, these diuretics may be insufficient to control the body fluid volume. Furthermore, the use of these diuretics poses the risk of electrolyte imbalance and renal dysfunction. Hillege et al. reported that impaired renal function (glomerular filtration rate) is a stronger predictor of mortality than impaired cardiac function in advanced chronic HF and that the former is associated with increased levels of N-terminal atrial natriuretic peptide (ANP). Thus, renalsparing water diuretics are preferable for the treatment of chronic HF.

Arginine vasopressin (AVP) is a 9-amino acid peptide secreted from the posterior pituitary, in response to high plasma osmolality and hypotension. AVP is known to play an important role in water metabolism by inducing water reabsorption at the renal collecting duct via the V2 receptor (V2R). AVP is also involved in the maintenance of blood pressure (BP) via the involvement of the V1a receptor (V1aR) in the vasculature. The role of AVP in chronic HF pathophysiology has been increasingly attracting attention. Several studies have shown that the plasma AVP level
was significantly higher in patients with HF and/or left ventricular (LV) dysfunction, thereby leading to volume overload\textsuperscript{7,8}.

Tolvaptan, a non-peptide AVP V\textsubscript{2}R antagonist, is a newly developed diuretic drug\textsuperscript{6,9}. This drug exerts an aquaretic effect by blocking the V\textsubscript{2}R at the renal collecting ducts and thereby inhibiting water reabsorption. A placebo-controlled study was performed to assess the clinical applicability of tolvaptan in patients with HF and reduced LV systolic function\textsuperscript{10}. The results indicated that the tolvaptan-treated patients had significantly lower rates of mortality or hospitalization for worsening HF than those administered the placebo. The tolvaptan group tended to show a better LV ejection fraction (LVEF) than the placebo group, but there was no significant effect of tolvaptan therapy on LV volumes observed during 1 year of therapy. Moreover, the large, multicenter trial, Efficacy of Vasopressin Antagonism in Heart Failure Outcome Study with Tolvaptan (EVEREST), revealed that chronic tolvaptan administration was safe and induced aquaresis, which was evidenced by a reduction in the body weight during the initial hospitalization for acute decompensated HF. Additionally, tolvaptan improved the dyspnea, although it neither improved nor worsened the primary outcome variable, which was mortality\textsuperscript{11-13}. Although V\textsubscript{2}R antagonism can aid in the management of congestion through aquaresis, it lacks natriuretic action and its cardiovascular actions remain unclear.

In the present study, we investigated whether tolvaptan is a more effective diuretic than furosemide in LV dysfunction, by using an experimental model of chronic LV dysfunction after MI. We obtained evidence that tolvaptan has the beneficial effect of improving cardiac remodeling in chronic LV dysfunction.
Methods

Animals and experimental design

Furosemide purchased from Sigma Chemical Co. (St. Louis, MO) and tolvaptan prepared by Otsuka Pharmaceutical Co., Ltd. (Tokushima, Japan) were used in this study. All procedures were performed in accordance with the Osaka City University animal care guidelines, which conform to the Guide for the Care and Use of Laboratory Animals published by the US National Institutes of Health (NIH Publication No. 85-23, revised 1996).

Male Wistar rats, aged 8–9 weeks and weighing 260 to 290 g, were purchased from CLEA Japan, Inc. (Tokyo, Japan). After administering pentobarbital sodium [50 mg·kg\(^{-1}\), intraperitoneally (ip)] as an anesthetic, MI was induced by the ligation of the left coronary artery, as described previously.\(^{14,15}\) Excluding the suturing of the coronary artery, the same surgical procedure was performed on a control group of rats. Ten weeks after MI induction, we measured the BP and heart rate (HR) of the rats by the tail cuff method (BP98A; Softron, Tokyo, Japan) and assessed cardiac function by echocardiography (SONOS 5500; Philips Medical Systems, Best, Netherlands). Because rats with less than 50% of LVEF were defined as “chronic LV dysfunction” in the present study, only two rats were excluded. On the basis of the findings, we separated the MI-affected rats into 6 groups: a non-treated vehicle (V) group, a group treated with 15 mg·kg\(^{-1}\)·day\(^{-1}\) of furosemide (F), 2 groups treated with 3 or 10 mg·kg\(^{-1}\)·day\(^{-1}\) of tolvaptan (TL or TH, respectively), and 2 groups treated with a combination of 15 mg·kg\(^{-1}\)·day\(^{-1}\) of furosemide and 3 or 10 mg·kg\(^{-1}\)·day\(^{-1}\) of tolvaptan (FTL or FTH, respectively). In the present study, we used 3 or 10 mg·kg\(^{-1}\)·day\(^{-1}\) of tolvaptan in the present study because these doses significantly increased urine volume in rats, but 1 mg·kg\(^{-1}\)·day\(^{-1}\) of tolvaptan did not changed in the previous report.\(^{16}\) Furthermore, diuretic action of tolvaptan 3 mg/kg seems to be as same as
15 mg·kg$^{-1}$·day$^{-1}$ of furosemide. Age-matched Wistar rats subjected to the sham operation were used as the control (C) group. The bait, which was prepared by Oriental Yeast Co. Ltd. (Tokyo, Japan), was mixed with the respective treatment agents and administered to the MI-affected rats. The rats were placed individually in metabolic cages, where they had free access to food and water such that assessment of the fluid and food intake and urine volume was possible.

Four weeks after treatment, the BP and HR of the rats were measured. Cardiac function was monitored by echocardiography under anesthesia, as described below. Immediately after echocardiography, the rat abdomen was cut open and a blood sample was collected from the inferior vena cava. The hearts were then immediately excised, and the ventricle was separated from the atrium and weighed. The infarct size was calculated as the ratio of the scar area to the entire cardiac muscle area, which was measured using a digital image analyzer. The ventricle was separated into the upper and lower portions, and then the upper portion of the left ventricle was divided into the marginal zone and non-infarcted zone; the specimens obtained were then immediately frozen in liquid nitrogen and stored at -80°C until further use. The lower portion was fixed in 10% formaldehyde overnight and embedded in paraffin. Other detailed procedures are described in Supplemental material.

**Statistical analysis**

All data are presented as means ± SEM or median ± interquartile range. Differences between group means were compared to the V group with Dunnett’s test by using StatView (SAS Institute, Inc., Cary, North Carolina, USA). The differences between the values before and after treatment were analyzed by using Wilcoxon signed-rank tests. The differences were considered statistically significant at a value of $P < 0.05$. 
Results

Effects of tolvaptan and furosemide on metabolic parameters

Nine rats for the C, F and FTL groups, 10 for the V and TH groups, and 11 for the TL and FTH groups were used in this study.

Mean BP (mBP) and HR at 10 weeks after MI induction ranged from 97 to 107 mmHg and from 352 to 393 bpm, respectively (data not shown). The measurements of the metabolic and hemodynamic parameters at 4 weeks after treatment are shown in fig 1. The food intake in all the groups was similar, and the planned treatment was successfully administered to all rats. The drinking and urine volume in the FTH group were significantly increased compared with the V group.

Effects of tolvaptan and furosemide on hemodynamic and organ weights

As shown in Table 1, there was no significant difference in the HR, mBP, and body weight (BW) between the treated groups and the V group. The infarct sizes of the V, F, TL, TH, FTL, and FTH groups were 35.8 ± 2.4, 35.8 ± 3.5, 40.0 ± 2.6, 35.0 ± 5.2, 36.0 ± 2.4, and 33.3 ± 1.7%, respectively (n.s., Figure 1-A). The values of ventricular weights/BW in the V group were significantly higher than those in the C group, while those in the FTL and FTH groups were significantly lower (2.3 ± 0.1 and 2.3 ± 0.1 mg·g⁻¹, respectively) than those in the V group (2.6 ± 0.1 mg·g⁻¹; Figure 1-B). Thus, the MI-induced increase in the value of ventricular weight/BW was inhibited by the combination therapy.

To evaluate the extent of organ congestion, we measured the lung and liver weights. In the present study, neither the lung weight nor the liver weight had a significant difference among the MI groups.
Blood and urine chemical analysis

The measurements of the blood and urine chemical parameters are shown in Table 2. The serum creatinine level did not show any significant difference. Although the urine sodium and potassium levels were lower in the FTH group than in the V group, the serum Na and K levels did not show any significant difference.

The brain natriuretic peptide (BNP) level, a marker of cardiac load, was significantly higher in the V group than in the C group, but the treatment groups did not differ significantly.

Cardiac function

Figure 2-A shows the LV end-diastolic volume (LVEDV), the LV end-systolic volume (LVESV), and LVEF measurements obtained by echocardiographic studies. Compared to the V group, the tolvaptan-treated groups had significantly lower LVEDV and LVESV and significantly higher LVEF. Furthermore, after 4 weeks of administration, tolvaptan produced a significant improvement in the LVEF (Figure 2-B), while furosemide did not result in any change in the LVEF.

Doppler echocardiographic analysis of the LV inflow pattern in each group is shown in Figure 2-C and Table 3. MI-induced restrictive inflow pattern tended to exhibit normal pattern by tolvaptan, although it was difficult to evaluate the LV inflow pattern quantitatively because the heart rates were not equalized adequately in the echocardiographic study. Especially, elevated early rapid filling (E) wave velocity by MI was significantly lowered in the TL group.

Estimation of macrophage infiltration and interstitial fibrosis in LV

The extent of macrophage infiltration in the marginal area of the infarct was estimated by
using an antibody against ED-1. Figure 3-A and B shows macrophage infiltration in the marginal area of the infarct. The increase of macrophage infiltration by MI was significantly suppressed in the FTH group.

The extent of interstitial fibrosis in the marginal zone of the infarct is shown in Figure 4-A and B. The extent of interstitial fibrosis in the tolvaptan-treated (TL, TH, FTL, and FTH) groups was significantly lower than the V group, while this effect was not shown in the F group.

**Effect of tolvaptan on cardiac gene expressions**

As shown in Figure 5, the mRNA expressions in the LV marginal area in each group of rats were measured by quantitative real-time RT-PCR (qRT-PCR) and differences between group means were compared to the V group with Dunnett’s test. mRNA expressions of ANP and BNP, which are factors closely associated with cardiac load, were increased by 36.1- and 3.8-fold ($P < 0.05$), respectively, by MI induction. The MI-induced upregulation of ANP or BNP expressions was significantly decreased in the TL and TH groups (Figure 5-A) or TH group (Figure 5-B), respectively.

MI-induced an 8.4- and 2.4-fold ($P < 0.05$) increase in the mRNA expressions of the monocyte chemoattractant protein-1 (MCP-1) and tumor necrosis factor (TNF)-α, which are factors closely related to cardiac inflammation. This increase was significantly lower in the TH and FTH groups (Figure 5-C) or TH group (Figure 5-D), respectively.

The mRNA expressions of the transforming growth factor (TGF)-β1 and collagen type III (Col III), which are factors closely associated with cardiac fibrosis, were increased by 3.4- and 10.1-fold ($P < 0.05$), respectively, by MI induction. This upregulation of TGF-β1 or Col-III was significantly decreased in the TH group (Figure 5-E) or FTH group (Figure 5-F), respectively.
Furthermore, the mRNA expression of V1aR and endothelin-1 (ET-1), which are factors closely associated with vasoconstriction, were significantly increased by MI induction. This upregulation of V1aR and ET-1 was significantly decreased in the tolvaptan-treated groups (Figure 5-G) or TH and FTH groups (Figure 5-H), respectively.

**Discussion**

This study revealed that tolvaptan may improve cardiac remodeling in LV dysfunction due to old MI. This is the first attempt to compare the effects of tolvaptan with those of furosemide and their combination in a rat model of LV dysfunction.

Previous clinical studies, such as EVEREST and the Effect of Tolvaptan on Hemodynamic Parameters in Subjects with Heart Failure (ECLIPSE) trial, have shown that tolvaptan increases urine output in a dose-dependent manner. On the other hand, no significant differences were reported for the secondary endpoints of BP, HR, systemic vascular resistance, or cardiac index. Notably, most of these patients were on concomitant medication. Therefore, from these studies alone, it is impossible to elucidate whether tolvaptan can independently improve LVEF in chronic HF patients.

In the present study using an experimental rat model of LV dysfunction, the influences of secondary factors affecting cardiac remodeling, such as BP, other medications, and infarct size were similar in all MI-induced groups. Thus, we could clearly evaluate the effects of tolvaptan alone in LV dysfunction. Furthermore, the medicated and non-medicated MI-affected groups did not differ significantly in terms of BW. After controlling the effects of these secondary factors, we found that the LVEF in the tolvaptan-treated groups was significantly greater than that in the furosemide-treated group. Additionally, tolvaptan also partially improved the increase of E wave
velocity by MI, suggesting that tolvaptan may also improve LV diastolic function because it has been reported that there is a weak correlation between LV end-diastolic pressure and E wave velocity and E deceleration time in MI rats. These findings suggest that the effect of tolvaptan in improving the LV dysfunction may not be entirely attributable to its volume-reducing effect. The ventricular weight in the combination therapy group was significantly lower than that in the untreated vehicle group as well as the monotherapy groups. This suggests that the addition of tolvaptan to the classical diuretic therapy (furosemide only) could improve cardiac remodeling after MI. Furthermore, tolvaptan with or without furosemide could prevent cardiac remodeling because tolvaptan alone could improve LVEF but furosemide alone failed.

Previous evidences suggest that the inflammatory response is a key component of the structural deterioration associated with post-MI remodeling of the LV. MCP-1, a C-C chemokine with potent chemotactic and activating effects on monocytes, is known to be a major contributor to the pathogenic role of inflammation in cardiovascular diseases. MCP-1 contributes to the progression of atherosclerosis and vascular remodeling. Recent reports have indicated that the expression of MCP-1 in the myocardium increases during the early phase of MI and that the targeted deletion or pharmacological inhibition of MCP-1 prevents early post-MI LV remodeling. Furthermore, the second phase of the inflammatory response occurs in the noninfarcted myocardium. It has been reported that MCP-1 expression and macrophage infiltration are increased in the noninfarcted region of the post-MI remodeled myocardium. Recent studies have shown that the marginal myocardial area might be a novel therapeutic target in the treatment of post-MI LV remodeling. Extension of the macrophage-mediated inflammation in the infarcted region might cause the inflammatory response in the marginal region, although the mechanism underlying the inflammatory response in the latter has not been
fully elucidated. In addition, geometric changes in hearts with LV aneurysm after MI are known to increase wall stress in the marginal region\textsuperscript{20}, and pressure overload-induced cardiac fibrosis is mediated through MCP-1 induction and macrophage accumulation\textsuperscript{27}. In the present study, ED-1 immunostaining and qRT-PCR revealed that tolvaptan significantly suppressed MI-induced macrophage infiltration and MCP-1 expression in the marginal myocardial area of the infarct.

Macrophages infiltrating the infarcted myocardium are known to produce a variety of inflammatory cytokines and growth factors, which in turn amplify the inflammatory response and promote myocardial fibrosis\textsuperscript{19,20}. In addition to its chemoattractant activity toward monocytes, MCP-1 itself is involved in the occurrence of fibrosis through the stimulation of fibroblast collagen expression via the generation of profibrotic cytokines\textsuperscript{28}. These findings suggest that MCP-1 might be a key mediator in the development of LV remodeling through macrophage infiltration and fibrosis in the marginal zone. Sirius red staining and qRT-PCR revealed that MI-induced interstitial fibrosis and fibrosis-related genes, such as TGF-β1 and Col III, was significantly inhibited by tolvaptan. We have, thus, for the first time, shown that tolvaptan has anti-inflammatory and antifibrotic activity in chronic stage of MI-induced LV dysfunction. On the other hand, furosemide does not have such beneficial effects.

Reports have indicated the existence of an interaction between the renin-angiotensin system (RAS) and MCP-1\textsuperscript{27,29}. Angiotensin II (Ang II) can induce the synthesis of MCP-1 both in vitro and in vivo, thereby suggesting that Ang II participates in the recruitment of inflammatory cells by increasing MCP-1 expression\textsuperscript{30}. On the other hand, inflammatory cells express all the components of the RAS\textsuperscript{31}, and the activity of the RAS is remarkably high during monocyte/macrophage differentiation\textsuperscript{32}. Therefore, Ang II-induced MCP-1 expression promotes the activation of inflammatory cells, which in turn can activate the RAS and increase local Ang
II generation, thereby contributing to the progression and perpetuation of inflammation. Hirano et al. reported that tolvaptan induces aquareasis, resulting in increased serum sodium levels, without affecting the RAS. In contrast, furosemide induces natriuresis, which results in decreased serum sodium levels and the activation of the RAS, thereby suggesting that furosemide may accelerate cardiac remodeling.

The direct effect of tolvaptan on the cardiac muscle is difficult to explain since tolvaptan is pharmacologically a V2R antagonist, and V2R is unknown to be expressed in cardiac muscles. LV V2R mRNA expression was undetectable in this model. (data not shown). However, our study showed that the ventricular weight was significantly lower in the group treated with a combination of furosemide and tolvaptan, and echocardiography showed significant improvement in the LVEF in the tolvaptan-treated groups. Further, since the groups did not differ in terms of BW, we can infer that the effect of tolvaptan may not be entirely explained by its volume-reducing effect. Some possibilities are considered to explain how tolvaptan works. Previous studies have shown that furosemide increases PRA, while that of the combination of furosemide and tolvaptan does not increase PRA. Unfortunately, furosemide did not elevate PRA in the present study of chronic phage after MI. The V1aR, which exists in cardiac or vascular smooth muscle cells, causes cardiac hypertrophy, blood vessel contraction, and cardiac remodeling. In the present study, MI-induced cardiac V1aR mRNA expression was significantly suppressed by the treatment of tolvaptan. Li et al. has shown that chronic V1aR activation in myocytes causes cardiac hypertrophy and the development of HF by using transgenic mice with myocyte-specific overexpression of V1aR, suggesting that tolvaptan may partially contribute to prevent cardiac dysfunction by down-regulation of V1aR of which activation plays a pivotal role during cardiac remodeling after MI. Very recent study also showed
that tolvaptan suppressed V1aR activation of myocardium in Dahl salt-sensitive rat and prevented not only the progression of LV dysfunction. Furthermore, hemodynamic stress or other neurohumoral factors might regulate local AVP system, though the mechanism has not been elucidated. Therefore, we investigated the effect of tolvaptan on cardiac ET-1 expression, one of neurohumoral factors. Interestingly, tolvaptan decreased MI-induced ET-1 expression. Taken together with a recent study that tolvaptan suppressed ET-1 expression of myocardium in Dahl salt-sensitive rat and prevented the progression of LV dysfunction, the underlying beneficial mechanism of tolvaptan may be partially related to the suppression of neurohumoral activation.

Study Limitations

Any invasive hemodynamic or telemetric analysis was not performed in this study. Cardiac function was estimated by echocardiography. It is unknown from our data whether tolvaptan has a cardioprotective effect on acute MI. The effect of tolvaptan on cardiac RAS is also unclear. Further studies are needed to elucidate the precise mechanism of the effects of tolvaptan and the efficacy of combination therapy with tolvaptan and a RAS inhibitor in chronic HF.

In conclusion, our present study provides the in vivo evidence showing the beneficial effect of tolvaptan in the improvement of cardiac dysfunction. This effect may be attributed to its anti-inflammatory and anti-fibrotic actions as well as its volume-reducing effect. We propose tolvaptan as a new therapeutic agent in LV dysfunction.
Acknowledgments

The authors thank Chiori Asahi for technical assistance.

Disclosures

H.F. is an employee of Otsuka Pharmaceuticals Co., Ltd.

References

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<th>F (n=9)</th>
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Value are median ±IQR. MI, myocardial infarction; C, sham-operated control rats; V, non-treated vehicle rats with MI; F, 15 mg·kg\(^{-1}\)·day\(^{-1}\) of furosemide-treated rats with MI; TL or TH, 3 or 10 mg·kg\(^{-1}\)·day\(^{-1}\) of tolvaptan-treated rats with MI, respectively; FTL or FTH, a combination of 15 mg·kg\(^{-1}\)·day\(^{-1}\) of furosemide and 3 or 10 mg·kg\(^{-1}\)·day\(^{-1}\) of tolvaptan-treated rats with MI, respectively. *P < 0.05 vs. V.
Table 2. Blood and urine chemical parameters

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<td>162.2 ± 3.6</td>
<td>152.2 ± 8.5</td>
<td>156.4 ± 7.9</td>
<td>151.0 ± 8.0</td>
<td>144.4 ± 8.2</td>
<td>161.8 ± 4.4</td>
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<td>plasma renin activity (ng•mL⁻¹•hr⁻¹)</td>
<td>5.3 ± 0.8</td>
<td>7.8 ± 2.7</td>
<td>6.4 ± 1.8</td>
<td>6.0 ± 1.6</td>
<td>4.9 ± 1.6</td>
<td>7.6 ± 1.6</td>
<td>5.9 ± 1.9</td>
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<td>Urine</td>
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<tr>
<td>sodium (mEq•L⁻¹)</td>
<td>97.5 ± 5.0</td>
<td>103.0 ± 7.4</td>
<td>107.2 ± 5.7</td>
<td>93.9 ± 6.0</td>
<td>94.4 ± 4.1</td>
<td>102.5 ± 4.5</td>
<td>81.2 ± 3.5 *</td>
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<tr>
<td>potassium (mEq•L⁻¹)</td>
<td>252.7 ± 13.9</td>
<td>272.1 ± 16.5</td>
<td>296.6 ± 10.5</td>
<td>263.1 ± 9.9</td>
<td>244.7 ± 11.5</td>
<td>267.4 ± 11.6</td>
<td>223.2 ± 12.8 *</td>
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<td>chlorine (mEq•L⁻¹)</td>
<td>116.2 ± 7.5</td>
<td>124.2 ± 7.7</td>
<td>125.9 ± 4.5</td>
<td>119.3 ± 10.2</td>
<td>117.2 ± 5.7</td>
<td>125.0 ± 5.4</td>
<td>103.5 ± 6.5</td>
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<td>osmolality (mOsm•kgH₂O⁻¹)</td>
<td>2045 ± 137</td>
<td>1966 ± 105</td>
<td>2087 ± 97</td>
<td>1916 ± 78</td>
<td>1717 ± 81</td>
<td>2043 ± 86</td>
<td>1709 ± 84</td>
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Value are mean ±SEM. MI, myocardial infarction; C, sham-operated control rats; V, non-treated vehicle rats with MI; F, 15 mg•kg⁻¹•day⁻¹ of furosemide-treated rats with MI; TL or TH, 3 or 10 mg•kg⁻¹•day⁻¹ of tolvaptan-treated rats with MI, respectively; FTL or FTH, a combination of 15 mg•kg⁻¹•day⁻¹ of furosemide and 3 or 10 mg•kg⁻¹•day⁻¹ of tolvaptan-treated rats with MI, respectively. *P < 0.05 vs. V.
Table 3. Echocardiographic measurements of left ventricular diastolic function at 4 weeks after each treatment

<table>
<thead>
<tr>
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<th>C (n=9)</th>
<th>V (n=10)</th>
<th>F (n=9)</th>
<th>TL (n=11)</th>
<th>TH (n=10)</th>
<th>FTL (n=9)</th>
<th>FTH (n=11)</th>
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<tr>
<td>early rapid filling (E) wave (cm•sec&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>77.2 ± 3.7 *</td>
<td>92.8 ± 4.6</td>
<td>88.3 ± 3.4</td>
<td>77.2 ± 3.9 *</td>
<td>87.0 ± 3.3</td>
<td>80.4 ± 3.8</td>
<td>87.5 ± 4.3</td>
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<tr>
<td>atrial contraction (A) wave (cm•sec&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>31.3 ± 3.0</td>
<td>26.9 ± 3.7</td>
<td>25.3 ± 2.1</td>
<td>29.0 ± 2.6</td>
<td>35.7 ± 4.4</td>
<td>26.9 ± 2.3</td>
<td>26.4 ± 3.0</td>
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<td>the ratio of E wave to A wave</td>
<td>2.80 ± 0.45</td>
<td>4.10 ± 0.60</td>
<td>3.65 ± 0.30</td>
<td>2.89 ± 0.47</td>
<td>2.90 ± 0.48</td>
<td>3.16 ± 0.32</td>
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<td>E deceleration (cm•sec&lt;sup&gt;-2&lt;/sup&gt;)</td>
<td>1523 ± 115 *</td>
<td>2116 ± 155</td>
<td>1809 ± 108</td>
<td>1377 ± 106 *</td>
<td>1695 ± 111 *</td>
<td>1698 ± 165</td>
<td>1670 ± 101 *</td>
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</table>

Values are mean ± SEM. MI, myocardial infarction; C, sham-operated control rats; V, non-treated vehicle rats with MI; F, 15 mg·kg<sup>-1</sup>·day<sup>-1</sup> of furosemide-treated rats with MI; TL or TH, 3 or 10 mg·kg<sup>-1</sup>·day<sup>-1</sup> of tolvaptan-treated rats with MI, respectively; FTL or FTH, a combination of 15 mg·kg<sup>-1</sup>·day<sup>-1</sup> of furosemide and 3 or 10 mg·kg<sup>-1</sup>·day<sup>-1</sup> of tolvaptan-treated rats with MI, respectively. *P < 0.05 vs. V.
Figure Legends

Figure 1. Infarct size and organ weights

(A) There was no significant difference in myocardial infarct size between the vehicle and the treated-groups. (B) The value of ventricular weight/body weight (BW) in the V group was significantly higher than that in the C group. This increase was significantly suppressed in the FTL and FTH groups. There was no significant difference between the treated groups and the V group in lung weight/BW (C) and liver weight/BW (D). C, sham-operated control rats; V, non-treated vehicle rats with MI; F, 15 mg·kg⁻¹·day⁻¹ of furosemide-treated rats with MI; TL or TH, 3 or 10 mg·kg⁻¹·day⁻¹ of tolvaptan-treated rats with MI, respectively; FTL or FTH, a combination of 15 mg·kg⁻¹·day⁻¹ of furosemide and 3 or 10 mg·kg⁻¹·day⁻¹ of tolvaptan-treated rats with MI, respectively. Values are mean ± SEM (n = 9 to 11). * P < 0.05 vs. V.

Figure 2. Echocardiographic measurements at 4 weeks after treatment

Graphs show echocardiographic assessments of LVEDV, LVESV, and LVEF in rats. LVEDV and LVESV were significantly higher in the V group than in the C group. They were significantly lower in the tolvaptan-treated groups than those in the V group. LVEF was significantly decreased in group V than in group C. Tolvaptan-treated groups had significantly greater improvement in LVEF than the V group. (B) Graphs showing changes in the LVEF in each group after treatment. Although groups V and F showed no significant change after treatment, LVEF was significantly improved by tolvaptan. Values are mean ± SEM. LVEDV, left ventricular end-diastolic volume; LVESV, left ventricular end-systolic volume; LVEF, left ventricular ejection fraction. Other abbreviations are the same as Figure 1 legend. Values are mean ± SEM (n = 9 to 11). * P < 0.05 vs. V.
Figure 3. Estimation of the extent macrophage infiltration

MI-induced macrophage infiltration in rats. (A) Representative photomicrographs of cross-sections of macrophage infiltration stained with ED-1 (dark brown cells) on left ventricular marginal area sections (original magnification ×400). Bar, 200 μm. (B) Quantitative results of macrophage infiltration (/hpf). Macrophage infiltration in the FTH group was lower than that in the V group. Abbreviations are the same as Figure 1 legend. Values are mean ± SEM (n = 9 to 11). * P < 0.05 vs. V.

Figure 4. Estimation of the extent of interstitial fibrosis

MI-induced interstitial fibrosis in rats. (A) Representative photomicrographs of the cross-sections showing myocardial interstitial fibrosis by staining left ventricular marginal area sections (original magnification ×200) with Sirius red (red). Bar, 500 μm. (B) Quantitative results of relative area of interstitial fibrosis (%). Tolvaptan-treated groups showed significant suppression of MI-induced interstitial fibrosis compared to the V group. Abbreviations are the same as Figure 1 legend. Values are mean ± SEM (n = 9 to 11). * P < 0.05 vs. V.

Figure 5. mRNA expression

Gene expressions in the marginal infarct region of the vehicle-treated and medicated rats, and left ventricle of the control rats. The bar graph shows the value of each mRNA, corrected for the GAPDH mRNA value. Mean values in the control rat group are represented as 1. All parameters of mRNA expressions were upregulated by MI induction. (A), (B) The MI-induced upregulation of ANP and BNP was significantly decreased in the TL and TH groups. (C), (D) MCP-1 or TNF-
α mRNA expression was significantly decreased in the TH and FTH groups or TH group, respectively. (E), (F) TGF-β1 or Col III mRNA expression was significantly decreased in the TH and FTH groups or FTL and FTH groups, respectively. (G), (H) MI-induced V1aR or ET-1 mRNA expression was also significantly decreased in the tolvaptan-treated groups or TH and FTH groups, respectively. ANP, atrial natriuretic peptide; BNP, brain natriuretic peptide; MCP-1, monocyte chemoattractant protein-1; TNF-α, tumor necrosis factor-α; TGF-β1, transforming growth factor-β1; Col III, collagen type III; V1aR, vasopressin V1a receptor; ET-1, endotheline-1. Other abbreviations are the same as Figure 1 legend. Values are mean ± SEM (n = 9 to 11). * P < 0.05 vs. V.
Experimental Procedures

Echocardiographic study

Transthoracic echocardiographic studies were performed on rats according to a previously described method\(^1\)\(^,\)\(^2\). In brief, rats were anesthetized with tiletamine (10 mg·kg\(^{-1}\), ip) and xylazine (10 mg·kg\(^{-1}\), ip). A two-dimensional short-axis view of the left ventricle was obtained at the level of the papillary muscles. The LVEF was calculated by measuring the LV end-diastolic volume (LVEDV) and the LV end-systolic volume (LVESV), by using a modified Simpson’s method. Pulsed wave Doppler spectra (early rapid filling (E) wave and atrial contraction (A) wave) of mitral inflow velocities were recorded from the apical four chamber view, with the sample volume placed near the tips of the mitral leaflets and adjusted to the position at which velocity was maximum and the flow pattern was laminar. The ratio of E wave velocity to A wave velocity (E/A ratio) and E deceleration were calculated.

ED-1 immunostaining and estimation of macrophage infiltration of the left ventricle

The area of interstitial macrophage infiltration in the marginal region of the infarct was measured using a previously described method\(^3\). In short, serial sections were stained with antibodies against ED-1 (Serotec Inc., NC), a marker for tissue-resident macrophages. Eight microscopic fields in each tissue block were examined for the presence of macrophages, and macrophage infiltration was expressed as the number of positive cells per high power field (×200).

Estimation of cardiac fibrosis

The area of interstitial fibrosis in the marginal area of the infarct was measured, as described
previously \(^4\)\(^5\). In short, 4-μm-thick sections were cut and stained with Sirius red stain for the measurement of the area with interstitial fibrosis. The area of interstitial fibrosis was calculated as the ratio of the sum of the total area of interstitial fibrosis to the sum of the total connective tissue area plus the area of cardiomyocytes in the marginal area of the LV. Each field was analyzed using image-analyzing software (Micro Analyzer, Japan Poladigital, Tokyo, Japan).

**RNA preparation and analysis**

RNA from the marginal area of the LV was isolated using ISOGEN (Nippon Gene, Toyama, Japan) \(^4\)\(^5\). To elucidate the gene expression levels, we subjected the RNA samples to quantitative real-time RT-PCR (qRT-PCR, 7500 Fast; Applied Biosystems, Carlsbad, CA). One-step qRT-PCR reactions were performed using 100 ng of total RNA per reaction. TaqMan primers and probes were designed using Primer 3 (v. 0.4.0); see Supplemental Table. For normalization, the transcript levels were compared to those of GAPDH.
Supplementary References


<table>
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<tr>
<th>Symbol</th>
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Gapdh, glyceraldehyde-3-phosphate dehydrogenase; Nppa, atrial natriuretic peptide; Nppb, brain natriuretic peptide; Ccl2, monocyte chemoattractant protein-1; Tnf, tumor necrosis factor-α; Tgfb1, transforming growth factor -β1; Col3, collagen type III; Avpr1a, V1a receptor; Edn1, endothelins-1.