In Vivo Ventricular Gene Delivery of a β-Adrenergic Receptor Kinase Inhibitor to the Failing Heart Reverses Cardiac Dysfunction

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Background—Genetic manipulation to reverse molecular abnormalities associated with dysfunctional myocardium may provide novel treatment. This study aimed to determine the feasibility and functional consequences of in vivo β-adrenergic receptor kinase (βARK1) inhibition in a model of chronic left ventricular (LV) dysfunction after myocardial infarction (MI).

Methods and Results—Rabbits underwent ligation of the left circumflex (LCx) marginal artery and implantation of sonomicrometric crystals. Baseline cardiac physiology was studied 3 weeks after MI; 5 x 10^11 viral particles of adenovirus was percutaneously delivered through the LCx. Animals received transgenes encoding a peptide inhibitor of βARK1 (Adeno-βARKct) or an empty virus (EV) as control. One week after gene delivery, global LV and regional systolic function were measured again to assess gene treatment. Adeno-βARKct delivery to the failing heart through the LCx resulted in chamber-specific expression of the βARKct. Baseline in vivo LV systolic performance was improved in Adeno-βARKct–treated animals compared with their individual pre–gene delivery values and compared with EV-treated rabbits. Total β-AR density and βARK1 levels were unchanged between treatment groups; however, β-AR–stimulated adenylyl cyclase activity in the LV was significantly higher in Adeno-βARKct–treated rabbits compared with EV-treated animals.

Conclusions—In vivo delivery of Adeno-βARKct is feasible in the infarcted/failing heart by coronary catheterization; expression of βARKct results in marked reversal of ventricular dysfunction. Thus, inhibition of βARK1 provides a novel treatment strategy for improving the cardiac performance of the post-MI heart. (Circulation. 2001;103:1311-1316.)

Key Words: gene therapy ■ receptors ■ heart failure ■ signal transduction

Molecular abnormalities associated with and implicated in the pathogenesis of ventricular dysfunction and heart failure (HF) present appealing targets for cardiac gene therapy. In particular, genetic manipulation of myocardial β-adrenergic receptor (β-AR) signaling offers a powerful way to alter myocardial function and represents a potential target that has recently elicited much attention.1 β-AR signaling abnormalities in the compromised and dysfunctional human heart have been well characterized and include a downregulation of β-ARs (specific for the β1-AR subtype), uncoupling of second-messenger systems, and an upregulation of the β-adrenergic receptor kinase (βARK1).2,3 βARK1 (also known as GRK2) is a member of the G-protein–coupled receptor kinase (GRK) family that phosphorylates agonist-occupied receptors, including cardiac β-ARs, triggering desensitization.4,5 Recent evidence has revealed that enhanced βARK1-mediated desensitization of myocardial β-ARs represents a maladaptive change in the failing heart, and thus βARK1 activity is a novel therapeutic target for potentially reversing ventricular dysfunction in cardiac disease states.

Importantly, βARK1 has been found to be a critical regulator of myocardial function.6 The expression and GRK activity of βARK1 in the heart has been found to be significantly elevated in human and animal models of HF, hypertrophy,7–9 and ischemia.10 Studies in genetically engineered mice have demonstrated the utility of βARK1 inhibition; expression of a βARK1-inhibitory peptide has prevented HF as the result of the knockout of the muscle LIM protein gene.8 The inhibitor of βARK1 (βARKct) is a peptide composed of the carboxyl-terminal 194–amino acid residues of βARK1, which competes with endogenous βARK1 for binding to the membrane-embedded βγ-subunits of activated

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heterotrimeric G-proteins, a process required for βARK1 activation.5,6

Recently, catheter-based methods have enabled in vivo adenovirally mediated gene transfer to normal and hypertrophied myocardium.6,13,14 These invasive methods in rats and rabbits have been developed to deliver transgenes globally to the beating heart in vivo. In a recent study, Adeno-βARKct was delivered globally to rabbit hearts at the time of the surgical induction of myocardial infarction (MI).6 Interest-

ingly, the acute inhibition of myocardial β-AR desensitiza-

In this study, we have taken a unique approach in that the βARKct transgene was not delivered to the heart until it was compromised in order to determine whether inhibition of βARK1 activity in the failing heart could reverse physiological left ventricular (LV) dysfunction. We have recently demonstrated in vivo adenovirally mediated transgene delivery in a ventricular-specific manner through selective percu-

taneous coronary catheterization and gene delivery.15 This technique was used in the present study, in which delivery of the βARKct transgene into the left circumflex coronary artery (LCx) targets LV-specific expression and the untreated RV can serve as an internal control to test the efficacy of the transgene. βARKct gene delivery to a dysfunctional heart is a critical step in validating βARK1 inhibition as a potential therapy for HF.

Methods

Adenoviral Constructs

The construction, production, and purification of adenoviral constructs with a second-generation E1/E4-deleted, replication-deficient adenovirus have previously been described.6 Three transgenes were used: βARKct (Adeno-βARKct), the marker transgene β-Galactosidase (Adeno-βGal), and an empty viral construct (EV).

Model of MI and Physiology

All animals received humane care, in compliance with guidelines prepared by the National Institutes of Health and according to protocols approved by Duke University. Adult male New Zealand White rabbits (~3 kg) were used in the study. Animals underwent a thoracotomy and implantation of sonomicrometric crystals along the midpapillary level were obtained for histological analysis and X-gal staining as described.6,13,14 In this study, we have taken a unique approach in that the βARKct transgene was not delivered to the heart until it was compromised in order to determine whether inhibition of βARK1 activity in the failing heart could reverse physiological left ventricular (LV) dysfunction. We have recently demonstrated in vivo adenovirally mediated transgene delivery in a ventricular-specific manner through selective percutaneous coronary catheterization and gene delivery.15 This technique was used in the present study, in which delivery of the βARKct transgene into the left circumflex coronary artery (LCx) targets LV-specific expression and the untreated RV can serve as an internal control to test the efficacy of the transgene. βARKct gene delivery to a dysfunctional heart is a critical step in validating βARK1 inhibition as a potential therapy for HF.

Intracoronary Gene Transfer

After the 3-week post-MI physiological assessment, 5×10¹¹ total viral particles (tvp) of adenovirus in 2 mL of PBS was injected into the LCx after percutaneous catheterization, as we have previously described.15 All rabbits received methylprednisolone (5.0 mg/kg IM per day) for 2 days after adenoviral delivery to limit the acute adenovirally mediated inflammatory response. Seven days after gene delivery (and 4 weeks after MI), cardiac function was studied in each rabbit as above.

Determination of Myocardial Transgene Expression and β-AR Signaling

To assess the efficacy of gene transfer to the infarcted rabbit heart, Adeno-βGal was delivered to the post-MI LCx as above. After excision of the heart, transverse cross sections of myocardium at the midpapillary level were obtained for histological analysis and X-gal staining as described.6,14,15 To assess βARKct transgene expression, ventricular RNA was isolated, and Northern blot analysis was performed by standard methods previously described.6,14 Determination of cardiac β-AR density and membrane adenylyl cyclase (AC) activity were performed on myocardial sarcolemmal membranes with standard methods previously described.6,14,15

Statistical Analysis

All data are expressed as mean±SEM. In vivo hemodynamic data were compared by means of a paired Student’s t test. Unpaired comparisons were made by ANOVA. For all analyses, a value of P<0.05 was considered to be statistically significant.

Results

In Vivo Intracoronary Delivery of Adenoviral Transgenes to Infarcted Rabbit Heart

LCx-mediated delivery of Adeno-βGal (5×10¹¹ tvp) to rabbits 3 weeks after MI resulted in robust expression of the transgene as determined by X-gal staining. Positive cardiomyocytes stained blue, and, as expected, were confined to the areas of the LV served by the vascular bed of the LCx (Figure 1A). Neither the septum nor the right ventricle (RV) stained blue, confirming a selective intracoronary delivery, and limited expression was found in the infarct zone (Figure 1A). Delivery of 5×10¹¹ tvp of Adeno-βARKct through the LCx to infarcted rabbit hearts also displayed an LV-specific distribution of the transgene mRNA. A representative Northern blot demonstrating βARKct transgene expression is shown in Figure 1B.

Improvement of LV Dysfunction in Post-MI Hearts After Adeno-βARKct Delivery

The functional consequences of selective intracoronary delivery of Adeno-βARKct in post-MI rabbits was determined by sonomicrometry and micromanometry catheterization. Animals were initially studied 3 weeks after LCx ligation to assess baseline post-MI function. We have previously shown that 3 weeks after infarction is the time at which hemodynamic dysfunction and other signs of HF are clearly evi-

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significantly elevated in MI animals compared with sham (data not shown), as has been previously described in this model.\textsuperscript{6,7} MI rabbits with significant regional and global LV dysfunction were treated by LCx catheterization with $5 \times 10^{11}$ tvp Adeno-βGal and were allowed to progress for 1 more week. Regional LV function was then measured, and Adeno-βARKct–treated rabbits showed marked and significant improvement in LV SS compared with values obtained just before gene delivery (Figure 2A). This near 100% improvement in LV SS was not seen in EV-treated MI rabbits. In fact, these rabbits displayed a significant decrease in LV SS 1 week after gene delivery (Figure 2B). In a separate subset of 3-week postinfarcted rabbits ($n=5$), 2D echocardiography was performed\textsuperscript{6} before and 1 week after Adeno-βARKct delivery. LV function as assessed by percent fractional shortening was significantly improved by βARK1 inhibition (before, 19.5 $\pm$ 1% versus after, 23 $\pm$ 2%, $P<0.05$, t test).

In vivo hemodynamics were evaluated by LV intracavitary pressure with micromanometer catheterization.\textsuperscript{6,7} There was a small improvement in contractility as measured by LV dP/dt\textsubscript{max}, after Adeno-βARKct delivery that did not reach statistical significance (Table). However, after βARKct expression, peak systolic blood pressure was significantly

![Figure 1. Transgene expression after LCx delivery. A, Representative whole mount of infarcted rabbit heart after treatment with $5 \times 10^{11}$ tvp Adeno-βGal. Area of thinned and infarcted myocardium is seen in LV free wall and represents superior aspect of infarct (asterisk and arrow). B, Expression of βARKct as confirmed by Northern blot analysis of RNA isolated from treated rabbit hearts.](image-url)
increased in the failing hearts after Adeno-βARKct treatment, which was also significantly greater than in EV-treated MI rabbits (Table). Interestingly, both LV EDP and HR did not significantly change after Adeno-βARKct delivery, whereas both of these parameters worsened (increased) in animals that received EV.

Molecular β-AR Signaling Changes Induced by βARKct Expression in Infarcted Heart

Three weeks after LCx ligation, a biventricular alteration of β-AR signaling was observed similar to that seen in other forms of HF. Samples from noninfarcted areas of the LV as well as RV samples from MI rabbit hearts had a decrease in total β-AR density. Figure 3 contains this data. Sham animals had normal LV β-AR density of ≈65 fmol per mg membrane protein, whereas LV and RV samples from 3-week post-MI rabbits that received Adeno-βARKct or EV had significantly downregulated β-ARs. In addition to β-AR density changes, post-MI rabbit hearts had elevated βARK1 expression (data not shown) and uncoupled AC signaling (see below) compared with sham control hearts. These alterations in βARK1 levels and β-AR signaling are consistent with those seen in our original study characterizing this rabbit HF model.7 One week after Adeno-βARKct or EV delivery to the infarcted LV, there was no significant change in βARK1 expression (data not shown).

Despite no change in β-AR density among treated animals, desensitization of β-ARs in the infarcted LV was significantly reversed after Adeno-βARKct delivery. Shown in Figure 4A is baseline and isoproterenol-stimulated AC activity found in myocardial membranes isolated from post-MI hearts 1 week after EV or Adeno-βARKct delivery. As shown, β-AR–stimulated AC activity was minimal in the infarcted hearts treated with EV, demonstrating severe uncoupling, whereas hearts expressing the βARK1 inhibitor had restored β-AR responsiveness (Figure 4A). In fact, as shown in Figure 4B, the β-AR responsiveness in βARKct-treated LVs was greater than what we found in membranes from noninfarcted sham LVs. The AC data are also interesting

Figure 2. Regional LV SS determined by sonomicrometry. A, LV SS values in Adeno-βARKct–treated or EV–treated MI rabbits before and after gene delivery. All MI rabbit hearts had significant decrease in LV SS as compared with sham control rabbits. *P<0.05 vs sham; †P<0.05 vs pre–gene delivery values; ‡P<0.05 vs Adeno-βARKct. B, Percent change in SS 1 week after gene delivery in EV–treated and Adeno-βARKct–treated animals. *P<0.05 vs pre–gene delivery values.

Figure 3. β-AR density values in MI and sham rabbit hearts. β-AR density was decreased after MI when compared with sham rabbits as measured 1 week after gene delivery. *P<0.05.

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Summary of In Vivo LV Performance as Determined by Micromanometer Catheterization

<table>
<thead>
<tr>
<th>Before Gene Delivery*</th>
<th>After Gene Delivery†</th>
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<tbody>
<tr>
<td></td>
<td>Adeno-EV</td>
</tr>
<tr>
<td>LV dP/dt\text{max}, mm Hg/s</td>
<td>2957±150</td>
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<tr>
<td>LV dP/dt\text{min}, mm Hg/s</td>
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<td>HR, bpm</td>
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<td>LVEDP, mm Hg</td>
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</tr>
<tr>
<td>LVSBP, mm Hg</td>
<td>66.8±1.8</td>
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*Hemodynamic measurements were obtained at baseline, 3 weeks after LCx ligation, and again 1 week after delivery of 5×10¹⁵ typ Adeno-βARKct or EV.† P<0.05 vs pregene delivery.
previously demonstrated that this model recapitulates the biventricular signaling abnormalities seen in HF. Furthermore, the power of the study design is that each animal serves as its own control, with an untreated RV as an additional source for comparison in individual animals.

Biochemically, the expression of βARKct in the LV improved β-AR signaling in the treated LV but not in the RV, which is a powerful demonstration of the ventricular specificity of our gene delivery methodology. In addition, LV AC activity in the Adeno-βARKct–treated animals was significantly higher than in EV-treated control rabbits, indicating that β-AR desensitization was attenuated as a consequence of βARKct expression. Interestingly, βARKct transgene expression did not alter βARK1 levels between the LV and RV of Adeno-βARKct–treated rabbits. This suggests that expression of βARKct at 1 week does not reverse the central neurohormonal or local mechanical stimulus responsible for βARK1 upregulation. Importantly, it provides further evidence that the improvement in AC activity and in vivo LV function is due to active inhibition of βARK1 by the βARKct rather than a relative decrease in βARK1 expression. Of course, because the βARKct acts through Gβγ inhibition, other signaling events mediated by Gβγ may also contribute to the positive therapeutic effects seen in HF. Moreover, other receptor systems that are targets for βARK1, in addition to β-ARs, may be involved.

We used both sonomicrometry and micromanometry to assess LV function in vivo in this small-animal model. Adeno-βARKct–treated animals had significant improvements in sonomicrometrically derived measures of LV systolic function. Moreover, there was a trend toward increased LV dP/dt max. Although all of the parameters are load-sensitive, the regional improvement in function as demonstrated by SS suggests a contractile benefit of βARKct expression. In fact, a significant decrease in LV SS was seen in control animals treated with the EV, suggesting an underlying decline in function secondary to catheterization or progression of dysfunction after 1 week of adenovirus delivery. The use of LV dP/dt max as a measure of global LV function may be limited by the variation in infarct size and may be more sensitive to loading conditions in this model than in normal myocardium. LV EDP did not significantly change in Adeno-βARKct–treated animals compared with EV-treated control rabbits, in which it increased further between 3 and 4 weeks after MI. This demonstrates that in MI rabbits not treated with the βARKct, LV dysfunction is progressing.

It bears mentioning that ventricular failure involves a myriad of receptor systems and abnormalities. It is unlikely that a single transgene can reverse all of the dysfunction and completely rescue the failing heart. However, of paramount importance is finding an efficacious transgene that is safe and does not ultimately damage myocardium. Perhaps more importantly, our catheter-based technique lends itself to other models of failure and hypertrophy and other intriguing questions may be answered with this technology. Thus, in addition to targeting myocardial β-AR signaling through βARK1 inhibition, as in this study, or exogenously increasing β-AR density, other worthwhile gene targets exist. The most promising appear to be manipulating myocardial Ca2+...
handling through the sarcoplasmic reticulum ATPase or phospholamban. An additional target that has recently emerged is manipulation of K channels in the cardiac sarcolemma, in attempts to alter repolarization abnormalities present in the failing heart.

Several lines of evidence point toward the actions of βARK1 being critically involved in the pathogenesis of HF. These include the fact that myocardial βARK1 expression is elevated in chronic human HF, contributing to the desensitization and downregulation of cardiac β-ARs. Because βARK1 expression and activity in the heart is also elevated in several animal models of disease, we have recently used transgenic mice with myocardium-specific expression of βARKct to further characterize the role of βARK1 in heart disease. The potential therapeutic usefulness of βARKct inhibition was demonstrated in the prevention of HF in a genetic mouse model of cardiomyopathy. This was accomplished by cross-breeding of the βARKct transgenic mouse with a mouse HF model induced by “knockout” of the muscle LIM protein gene. Before the current study, adenosively mediated transfer of the βARKct transgene to failing cardiomyocytes isolated from rabbits in HF resulted in the reversal of β-AR signaling abnormalities. In addition, we have recently delivered Adeno-βARKct to rabbit hearts at the time of LCx ligation and MI and found that βARK1 inhibition prevented the β-AR signaling abnormalities present acutely after MI and thereby significantly delayed the development of HF.

This study provides unique insight into one approach for therapeutic cardiac gene therapy. Adenoviral vectors encoding βARKct have allowed us to test the hypothesis that genetic manipulation of β-adrenergic signaling in adult myocardium may improve systolic function in the setting of acquired LV dysfunction. No reports have previously examined this question. Our model demonstrates that noninfarcted yet dysfunctional myocardium may be rescued at a molecular level. Thus, βARK inhibition may represent a novel form of molecular ventricular assistance.

The fact that β-AR signaling is severely impaired in the failing heart no doubt provokes hyperactivity of the sympathetic nervous system; thus, a pathological cycle is perpetuated. Our hypothesis is that by relieving a brake on the system (ie, βARK1), cardiac function can be improved, which can also chronically lead to the dampening of sympathetic overdrive, thus reversing the vicious cycle. Therefore, unlike β-agonists that can improve contractility acutely but further uncouple β-ARs through chronic stimulation, inhibition of βARK1 begins to return β-ARs to a more normal state of signaling. This may not only lead to the acute improvement in cardiac performance but also can allow the compromised myocardium to recover from the chronic bombardment of catecholamines, which characterize the decompensated state. The present study, demonstrating the effectiveness of the βARKct in reversing functional signaling abnormalities in the post-MI heart, adds weight to our recent study demonstrating that inhibition of βARK1 at the time of LCx ligation can prevent acute β-AR signaling abnormalities and delay the development of HF. Both studies support our hypothesis that βARK1 is an important HF target. This novel therapeutic strategy can be approached either through gene therapy with the βARKct or through the development of pharmaceutical inhibitors of the βARK1 Гβγ interaction.

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