Increased Cardiac Adenylyl Cyclase Expression Is Associated With Increased Survival After Myocardial Infarction

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Background—Cardiac-directed expression of adenylyl cyclase type VI (ACVI) in mice results in structurally normal hearts with normal basal heart rate and function but supranormal responses to catecholamine stimulation. We tested the hypothesis that increased left ventricular (LV) ACVI content would increase mortality after acute myocardial infarction (MI).

Methods and Results—Transgenic mice with cardiac-directed ACVI expression and their transgene-negative littermates (control) underwent coronary ligation, and survival, infarct size, and LV size and function were assessed 1 to 7 days after MI. Mice with increased ACVI expression had increased survival (control 41%, ACVI 74%; P=0.004). Infarct size and myocardial apoptotic rates were similar in ACVI and control mice; however, ACVI mice had less LV dilation (P<0.001) and increased ejection fractions (P<0.03). Three days after MI, studies in isolated perfused hearts showed that basal LV +dP/dt was similar, but graded dobutamine infusion was associated with a more robust LV contractile response in ACVI mice (P<0.05). Increased LV function was associated with increases in cAMP generation (P=0.0002), phospholamban phosphorylation (P<0.04), sarcoplasmic reticulum Ca2+-ATPase (SERCA2a) affinity for calcium (P<0.015), and reduced AV block (P=0.04).

Conclusions—In acute MI, increased cardiac ACVI content attenuates adverse LV remodeling, preserves LV contractile function, and reduces mortality. (Circulation. 2006;114:388-396.)

Key Words: gene therapy • receptors, adrenergic, beta • cAMP • coronary disease • signal transduction

Cardiac-directed expression of adenylyl cyclase type VI (ACVI) results in structurally normal hearts with normal basal heart rate and function but supranormal responses to catecholamine stimulation.1 The use of β-adrenergic receptor (βAR)-stimulating agents, which increase intracellular cAMP, may cause sustained myocardial ischemia due to increased myocardial oxygen demand or may induce ventricular arrhythmias. Whether increased cardiac content of ACVI has a deleterious effect on myocardial ischemia is unknown; however, it is reasonable to expect that increased cAMP generation and hence contractile force, with attendant exacerbation of oxygen demand/supply imbalance, would have detrimental consequences in the setting of myocardial infarction (MI) by increasing border zone injury and extending infarct size. Here, we test the hypothesis that increased left ventricular (LV) ACVI content would increase mortality after acute MI. To test this hypothesis, MI was induced by proximal left coronary ligation in transgenic mice with cardiac-directed expression of ACVI and their transgene-negative littermates. We then assessed survival, infarct size, LV size and function, apoptosis rates, cAMP production, calcium handling, and incidence of arrhythmias.

Methods

Animals

Animal use and care were in accordance with institutional and National Institutes of Health guidelines. Transgenic mice (C57BL/6) were generated with murine ACVI cDNA under direction of the α-myosin heavy chain promoter to produce cardiac-directed expression of ACVI.1 Male and female ACVI transgenic mice (4±1 months old; n=108) and their age-matched transgene-negative littermates (control; n=107) were used. Gene presence was confirmed with genomic DNA purified from tail tips. Mice were housed with free access to food and water and exposed to 12-hour light/dark cycles.

Myocardial Infarction

MI was induced by permanent ligation of the left coronary artery as described previously.2
Survival Study

ACV transgenic mice and their transgene-negative littermates underwent acute MI in a randomized, blinded study. This study was designed to determine the 7-day survival of mice after MI; therefore, mice that did not survive the surgical procedure were not included in the analysis. Eighty-four mice (42 ACV; 42 control) underwent surgery for the survival study. Sixteen mice (8 ACV; 8 control) died of surgical complications: 4 mice (2 ACV; 2 control) died before coronary ligation, 7 (4 ACV; 3 control) died after coronary ligation but before extubation, and 5 (2 ACV; 3 control) died immediately after extubation. The remaining 68 mice, consisting of 34 ACV mice (21 males, 13 females) and 34 control mice (22 males, 12 females), were enrolled.

Infarct Size

Twenty-four hours after MI, area at risk and infarct size were assessed (n=7 per group) with the Evans blue and 2,3,5-triphenyl-tetrazolium chloride (TTC) staining technique. This time point was selected to avoid differences in hypertrophy of the uninfarcted wall that might result from differences in LV ACV expression. Measurements of the proportion of LV infarcted were therefore not confounded by differences in remodeling between groups that might occur between days 2 and 7. Methods to evaluate infarct size in mice 24 hours after coronary occlusion have been established.

Animals were anesthetized, intubated, and connected to a rodent ventilator. Evans Blue (1%) was injected retrogradely (via catheter) into the carotid artery to delineate the area at risk. Hearts were excised and immersed in 1% agarose and sectioned perpendicular to the long axis into 1-mm slices, which were incubated in 1.0% TTC (Sigma; St. Louis, Mo) for 5 minutes at 37°C. Each slice was weighed and photographed under a microscope. LV area, at risk, and area of infarction for each slice were determined by planimetry with ImagePro software (Image Processing Solutions, Inc, North Reading, Mass).

In Vivo Hemodynamics

LV pressure was measured in intact mice, as described previously, 3 days after MI (8 ACV, 7 control). Mice were anesthetized with ketamine (100 mg/kg IP) and xylazine (2.5 mg/kg IP). After LV pressures were recorded, bilateral vagotomy was performed. LV pressure was recorded at baseline and 45 seconds after bolus injection of isoproterenol (1, 10, and 100 pg/g in 100 μL) at 5-minute intervals. Peak rates of LV pressure development (dP/dt) and relaxation (LV –dP/dt) were determined after acquisition of LV pressure signals at a sampling rate of 3000 per second (Daq DI-400, WinDaq software; Dataq Instruments, Akron, Ohio). Ten sequential beats were averaged for each measurement. Data were recorded and analyzed in a blinded manner.

Ex Vivo Hemodynamics

Ex vivo cardiac function in response to βAR stimulation was assessed in isolated perfused hearts, as described previously. 3 Days after MI (n=6 per group). Dobutamine was delivered (1, 3 and 10 μmol/L) at 5-minute intervals as LV pressure was recorded, and LV +dP/dt and –dP/dt were determined. Data were recorded and analyzed in a blinded manner.

Echocardiography

Echocardiography was performed with a 16-MHz probe (Sonos 5500, Philips, Bothell, Wash) in mice 1 day before and 7 days after MI. LV ejection fraction was calculated by the area-length method, which has been validated in rodents and humans. 5

Apoptosis

Terminal dUTP nick end-labeling (TUNEL) assays were performed on LV samples with the CardioTACS In Situ Apoptosis Detection Kit (R&D Systems, Minneapolis, Minn) as described previously. 6 Seven days after MI, the heart was arrested in diastole, excised, and sliced into 3 sections perpendicular to the long axis. The slices were fixed in 3.7% formaldehyde solution for 24 hours, paraffin embed-

ded, sectioned (5 μm), and mounted on glass slides. Photomicrographs were obtained with a digital camera mounted on an inverted microscope. Images of 6 to 8 contiguous sections across the LV wall were obtained at the different levels (apex, mid ventricle, and base) to measure the number of TUNEL-positive cardiac myocyte nuclei in the peri-infarct border and uninfarcted remote zones, where myocyte apoptosis is reported to occur after MI. 7 Digital images were evaluated with NIH Image to count TUNEL-positive-stained nuclei and total number of nuclei in a nuclease pretreated section from the same region. Only nuclei that were clearly located in cardiac myocytes were scored. The area of each section was planimetrized to calculate the average density of nuclei (nuclei per μm²), TUNEL-positive–stained nuclei (per μm²), and rate of TUNEL-positive nuclei (per 10⁶ nuclei).

Western Blot Analysis

LV samples were homogenized and underwent Western blot analysis as described previously. 8–10 Antibodies to Gαs, ACV, βAR, and β2AR were purchased from Santa Cruz Biotechnology (Santa Cruz, Calif); antibodies to phospholamban and sarcoplasmic reticulum Ca²⁺-ATPase (SERCA2a) were purchased from Affinity BioReagents (Golden, Colo); antibody to Ser16 site phosphorylated phospholamban was purchased from Upstate (Charlestown, Va). Pre- previous studies have shown high specificity for these antibodies. 8–10

LV cAMP Generation

Samples of viable LV were homogenized and cAMP levels determined before (basal) and after stimulation by 10 μmol/L NKH477, a water-soluble forskolin derivative, as described previously. 10

Calcium Uptake

Samples of viable LV were homogenized, and the initial rate of ATP-dependent sarcoplasmic reticulum (SR) calcium uptake was measured by the modified Millipore (Billerica, Mass) filtration technique as described previously. 5

Telemetry

Eight ACV transgenic mice and 8 control mice underwent telemetry implantation, as described previously. 11 Mice recovered for ≥5 days. After baseline ECG was recorded for 24 hours, MI was induced. Telemetry data were recorded with Dantec A.R.T. acquisition software version 3.10 (Data Sciences International, Inc, St. Paul, Minn) until death or for 7 days after MI. ECG data were analyzed with ECG Auto software version 1.5.12 (EMKA Technologies, Falls Church, Va), and arrhythmic events, including premature ventricular beats and second- or third-degree AV block, during the first 24 hours after MI were visually identified (blinded to group). The agonal rhythm was assessed from the ECG data acquired 1 hour before asystole. At least 95% of the data for each mouse were adequate for analysis.

Propranolol Study

We asked whether propranolol would influence survival, LV function, or apoptosis after MI. Using normal mice (C57BL/6) with implanted telemetry units (n=4), we found that mean heart rate response to isoproterenol (1 mg/kg IP) was 76 bpm; propranolol (1 mg/kg IP) blocked this heart rate response, as reported previously. 11,12 Forty-two mice (21 ACV, 21 control) underwent MI, but animals received propranolol (1 mg/kg IP) 30 minutes before MI and every 12 hours until death or 7 days after infarction. Five mice died of surgical complications (3 ACV, 2 control); the remaining 37 (18 ACV, 19 control) were enrolled in the mortality study. A subset of each group underwent echocardiography (11 ACV, 10 control) and measurement of LV apoptosis (5 ACV, 5 control).

Statistical Analysis

Results are shown as counts or as mean±SD. Group comparisons were made with Fisher exact test for nominal data and Mann-Whitney U tests for continuous data. Survival curves were computed
by the Kaplan-Meier method and compared with the log-rank test. EC50 values were estimated and compared with the 3-parameter sigmoidal model. Phospholamban phosphorylation content was compared with a Welch $t$ test. The null hypothesis was rejected if $P < 0.05$. Analyses were performed with SPSS for Windows (SPSS, Inc) and EC50 calculations made with GraphPad Prism (GraphPad Software, Inc).

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

Results

Survival Study
Kaplan-Meier analysis revealed increased survival 7 days after MI (the primary end point of the study) in ACV1 mice (Figure 1). ACV1 mice had a survival rate of 74% compared with 41% for the transgene-negative group (n=34 for each group, $P=0.004$). All animals had anterior-wall MI at necropsy. LV rupture was found in 3 ACV1 mice and 3 control mice.

Infarct Size
Figure 2 shows the delineated area at risk and infarct size in hearts stained with Evans Blue and TTC 24 hours after left coronary artery ligation. The area at risk was not different between control and ACV1 mice (control 51±6%; ACV1 54±6%; n=7 for each group; $P=0.46$). Infarct size was similar in both groups (control 49±7%; ACV1 51±7%; n=7 for each group; $P=0.54$). The proportion of infarction related to the area at risk was also similar in both groups (control 96±2%; ACV1 96±3%; n=7 for each group; $P=0.71$). Histological examination with TTC staining showed that there was no necrosis in the area of the AV node.

In Vivo Hemodynamics
There were no differences in heart rate, LV $+dP/dt$, and LV $-dP/dt$ between the ACV1 and control groups after vagotomy (Table 1). After vagotomy, heart rate increased to the same extent in both groups, but LV systolic pressure was higher in ACV1 mice ($P=0.029$). ACV1 mice also showed increased LV $+dP/dt$ ($P=0.021$) and decreased LV $-dP/dt$ ($P=0.029$). These changes persisted after vagotomy in both groups (Figure 3). These data indicate that an increase in cardiac ACV1 content increases LV contractility and relaxation 3 days after MI.

Ex Vivo Hemodynamics
To provide a means to evaluate LV function isolated from reflex activation, the influence of neurohumoral input, and anesthetic agents, hearts were isolated from ACV1 and control mice 3 days after MI. Basal LV systolic pressure was higher in ACV1 mice ($P=0.037$). Basal LV $+dP/dt$ was similar in both groups (control 2136±567 mm Hg/s, ACV1 2500±446 mm Hg/s; n=6 for each group; $P=0.42$). Graded dobutamine infusion revealed increased LV systolic pressure (Figure 4). Basal heart rate did not differ between groups ($P=0.132$).

Echocardiography
Table 2 shows echocardiographic findings before and after MI. Before MI, there were no differences in heart rate, LV dimensions, wall thickness, and LV function between ACV1 and control mice, as anticipated from our previous report. Seven days after MI, heart rate and posterior wall thickness were significantly increased in ACV1 mice (Table 2). The increase in LV end-diastolic dimensions and thickening in the ACV1 mice was associated with a decrease in LV ejection fraction (Table 2). The LV weight was increased in ACV1 mice compared with control mice ($P=0.037$). IVC was also increased in ACV1 mice ($P=0.029$).

Figure 1. Kaplan-Meier curve showing survival after MI in ACV1 mice (n=34) and control (CON) mice (n=34). Mortality at 7 days was significantly reduced in ACV1 mice ($P=0.004$).

Figure 2. A, Transverse sections of LV at the midventricular level 24 hours after MI; 1% Evans Blue and 1% TTC. B, Area at risk was similar in control (CON) and ACV1 mice. C, Infarcts were large (50±2%) and were not different between groups. Bars represent mean value; error bars denote 1 SD. n=7 for each group.
decreased in both groups; however, LV end-diastolic diameter \( (P<0.001) \) and LV end-systolic diameter \( (P<0.001) \) were smaller in ACV1 mice, which indicates reduced chamber dilation. In addition, ACV1 mice showed increased LV ejection fractions \( (P=0.034) \). These data suggest that cardiac-directed ACVI expression attenuates LV dilation and improves LV contractile function after MI.

**Apoposis**
A \( >13 \)-fold increase of TUNEL-positive nuclei was observed in the peri-infarct border zone compared with the noninfarcted remote zone for both groups (Figure 5). There were no differences in rates of myocardial apoptosis between control and ACV1 mice in the border zone 7 days after MI (control \( 6719\pm1729 \) and ACV1 \( 495\pm2671 \) positive nuclei per \( 10^6 \) cells; \( n=7 \) for each group; \( P=0.81) \). The apoptotic rate in the remote zone was also similar in both groups (control \( 472\pm151 \) and ACV1 \( 496\pm156 \) positive nuclei per \( 10^6 \) cells; \( n=7 \) for each group; \( P=0.71) \).

**LV ACVI, Gαs, β1AR, and β2AR Expression**
We found a \( 17 \)-fold increase in ACVI protein content in LV samples from ACV1 mice versus control \( (P<0.008; \) Figures 6A and 6B), and AC-stimulated cAMP generation was 4.2-fold higher in viable LV samples from ACV1 versus control mice 7 days after MI \( (P=0.0002; \) Figure 6C). Cardiac-directed ACVI expression did not affect basal AC activity. We found no group differences in β1AR protein content (control \( 610\pm92 \) and ACV1 \( 704\pm142 \) densitometry units; \( n=8 \) for each group; \( P=0.23) \) or β2AR protein content (control \( 129\pm31 \) and ACV1 \( 167\pm67 \) densitometry units; \( n=8 \) for each group; \( P=0.23) \). Similarly, we found no group difference in Gαs protein content (control \( 389\pm24 \) and ACV1 \( 392\pm65 \) densitometry units; \( n=8 \) for each group; \( P=0.72) \).

**Calcium Uptake**
To elucidate the mechanism by which increased cardiac ACVI protein leads to increased LV contractile function in the setting of acute MI, we assessed LV calcium signaling, a major regulator of contractile function. Western blotting analyses showed that LV SERCA2a protein content did not differ between groups (control \( 2176\pm757 \) and ACV1 \( 1819\pm642 \) densitometry units; \( n=8 \) for each group; \( P=0.57) \).

### TABLE 1. Hemodynamic Data: In Vivo Study

<table>
<thead>
<tr>
<th></th>
<th>Control (n=7)</th>
<th>ACV1 (n=8)</th>
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<tr>
<td></td>
<td>Pre vagotomy</td>
<td>Post vagotomy</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Pre vagotomy</td>
<td>Post vagotomy</td>
</tr>
<tr>
<td>HR, bpm</td>
<td>252±113</td>
<td>240±75</td>
<td>0.999; 0.613; 0.779</td>
</tr>
<tr>
<td>LVP, mm Hg</td>
<td>72±8</td>
<td>74±14</td>
<td>0.955; 0.006; 0.029</td>
</tr>
<tr>
<td>LVEDP, mm Hg</td>
<td>8±4</td>
<td>11±5</td>
<td>0.232; 0.281; 0.955</td>
</tr>
<tr>
<td>LV + dP/dt, mg Hg/s</td>
<td>3505±994</td>
<td>3222±1121</td>
<td>0.536; 0.002; 0.021</td>
</tr>
<tr>
<td>LV − dP/dt, mg Hg/s</td>
<td>2887±771</td>
<td>2706±836</td>
<td>0.694; 0.006; 0.029</td>
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HR indicates heart rate; LVP, LV systolic pressure; and LVEDP, LV end-diastolic pressure. Data are mean±SD. \( P \) values are for group differences for prevagotomy (first value), postvagotomy (second value), and change (third value).

Mean heart rate, measured with ambulatory telemetry monitors in unanesthetized animals, was similar in control and
ACVI mice before MI (control 560±34 bpm, ACVI 579±52 bpm; n=8 for each group; P=0.33), as anticipated from a previous report.11 After coronary occlusion, we observed ST-segment elevation and subsequent formation of abnormal Q waves in each animal (Figure 8). Mean heart rate after MI was comparable between control and ACVI mice (control 492±84 bpm, ACVI 489±110 bpm; n=8 for each group; P=0.88). Total number of premature ventricular complexes during the first 24 hours after MI was not different (control 2000±1714, ACVI 5056±6581; n=8 for each group; P=0.57). The proportion of animals showing nonsustained ventricular tachycardia, a frequent occurrence after MI, was not different between groups (control 50%, ACVI 50%; P>0.99). ACVI mice had a reduced incidence of second- or third-degree AV block during the first 24 hours after MI (control 75%, ACVI 13%; P=0.02). In this subset of animals with telemetry units, 2 of 8 ACVI transgenic mice versus 4 of 8 control mice died by the seventh day after MI; LV rupture was found in 1 ACVI and 1 control mouse. The agonal rhythm consistently was marked bradycardia with progressive high-grade AV block (Figure 8). Sustained ventricular tachycardia or fibrillation did not occur.

Propranolol Study

Table 3 summarizes the results from the secondary study on the effects of propranolol compared with ACVI. Propranolol and ACVI had similar survival advantages (propranolol: 63% survival, n=19; ACVI: 74% survival, n=34; P=0.44) and similar effects on LV ejection fraction (propranolol: 20±6%, n=10; ACVI: 25±6%, n=11; P=0.09). Apoptosis rates were similar in propranolol and ACVI groups in both border and remote zones (Table 3).

Discussion

In acute MI, increased cardiac myocyte ACVI expression is associated with reduced mortality (56% reduction; P=0.004). The unexpected favorable effect on mortality conferred by ACVI expression led us to seek mechanisms for increased survival. We therefore measured infarct size, extent of dysfunction, degree of remodeling, apoptosis rates, cAMP generation, calcium handling, and incidence of arrhythmic events.

We asked whether increased cardiac ACVI content influenced infarct size, because LV contractile function and mortality after MI are closely linked with infarct size. There were no differences in area at risk or infarct size in a subgroup of ACVI and control mice. Infarct size averaged 50% of the LV and was not affected by increased cardiac ACVI expression (Figure 2). Evaluation of LV function was performed 3 days after MI, when survival rates were comparable between the 2 groups. We measured LV function using 2 approaches: in vivo (in anesthetized, ventilated animals) and ex vivo (isolated, perfused, isovolumically contracting hearts). This was done because there are advantages and shortcomings to either approach. The apparent differences in basal LV +dP/dt and LV −dP/dt observed in the “unstimulated” state (no

**Figure 4.** Cardiac responsiveness to βAR stimulation ex vivo, assessed 3 days after MI. A, LV systolic pressure (LVSP) was increased in mice with cardiac-directed ACVI expression. B, Mice with cardiac-directed ACVI expression showed nonsignificant increases in LV +dP/dt. C, Heart rates were similar in control and ACVI mice. ● indicates mean values from 6 control mice; ○, mean values from 6 ACVI mice; and HR, heart rate. Error bars denote 1 SD. *P<0.05 for comparisons of specific dose.

<table>
<thead>
<tr>
<th>TABLE 2. Echocardiographic Data</th>
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<tbody>
<tr>
<td><strong>Control</strong> (n=11)</td>
</tr>
<tr>
<td>Before MI</td>
</tr>
<tr>
<td>HR, bpm</td>
</tr>
<tr>
<td>LVEDD, mm</td>
</tr>
<tr>
<td>LVESD, mm</td>
</tr>
<tr>
<td>A Wh, mm</td>
</tr>
<tr>
<td>P Wh, mm</td>
</tr>
<tr>
<td>LVEF, %</td>
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</table>

HR indicates heart rate; LVEDD, LV end-diastolic diameter; LVESD, LV end-systolic diameter; A Wh, anterior-wall thickness; P Wh, posterior-wall thickness; and LVEF, LV ejection fraction.

Data are mean±SD.

P values are group differences before MI (first value), after MI (second value), and change (third value).
isoproterenol infused) may not reflect a true basal state, because surgical intervention, anesthesia, and mechanical ventilation are known to increase endogenous catecholamine release, thereby obfuscating assessment of basal heart function.

In the in vivo studies, we found increased LV +dP/dt and reduced LV −dP/dt in ACV_{I} mice after vagotomy and after βAR stimulation, which indicates that increased cardiac ACV_{I} content increases global LV contractile function and relaxation in the setting of MIs of equivalent size. Vagotomy had similar effects on heart rate in both groups, which suggests that vagal tone was similar. Thus, the differences we saw in LV dp/dt were not likely to be the result of variations in vagal tone. We previously reported that there were no differences in heart rate variability or response to atropine between ACV_{I} transgene-positive and -negative mice in studies conducted in conscious ambulatory mice with telemetry, which indicates that increased cardiac ACV_{I} expression does not alter vagal tone.

To evaluate LV function isolated from reflex activation, neurohumoral input, and anesthesia, we assessed LV contractile function in isolated perfused hearts. These studies showed that basal LV +dP/dt was unchanged (Figure 4); however, βAR stimulation was associated with more robust LV systolic pressure development in ACV_{I} mice. Increased cardiac reserve would be expected to confer a survival advantage and is a likely mechanism for reduced mortality.

Echocardiography was used to assess LV size and function in vivo. There was reduced LV dilation 7 days after MI in ACV_{I} mice, which suggests a protective effect of increased cardiac ACV_{I} content on adverse LV remodeling after acute MI. Both infarct expansion and dilation of noninfarcted viable regions play a role in the remodeling process that occurs early after MI. Infarct size has a great impact on this deleterious process, but in the present study, infarct sizes were not different between groups. The precise mechanisms...
by which increased expression of ACVt attenuates adverse LV remodeling remain uncertain. Increased function in the non-infarcted viable region may contribute to preservation of global LV function and may decrease activation of the renin-angiotensin-aldosterone system and thereby reduce LV chamber dilation. Reduced LV dilation after MI would be expected to confer a survival advantage14 and provides a second contributing mechanism for reduced mortality.

Abnormal LV calcium handling is a hallmark of heart failure. Both defective calcium uptake by SERCA2a and defective calcium release through the SR calcium release channel ryanodine receptor 2 (RyR2) occur in clinical and animal models of heart failure.9,15,16 In the present study, we found that ACVt expression was associated with increased SERCA2a affinity for calcium (Figures 7C and 7D). This improvement of calcium uptake by ACVt was associated with increased phosphorylation of phospholamban at Ser16; protein contents of phospholamban and SERCA2a were unchanged (Figures 7A and 7B). Expression of a Ser16 pseudophosphorylated mutant of phospholamban in an animal model of cardiomyopathy was reported to increase calcium uptake and attenuate heart failure progression.17 The present data provide a mechanism by which ACVt has beneficial effects on LV function and survival after MI.

Because myocardial apoptosis may contribute to the progression of LV remodeling and heart failure, we assessed myocardial apoptosis in the remote and the border zones 7 days after MI. There were no significant differences between groups in apoptotic rates in either region, which indicates that the salutary effects of increased cardiac ACVt content on LV remodeling after acute MI are not the result of reduced apoptosis. Nonetheless, it is noteworthy that increased cardiac ACVt expression does not alter myocyte apoptosis, because this result is in contrast to cardiac-directed expression of β1AR or Gzβz, which is associated with increased myocyte apoptosis and heart failure.12,18,19

We previously showed that mice with cardiac-directed expression of ACVt have ambulatory heart rates similar to transgene-negative littermates.11 In the present study, we found that increased cardiac ACVt expression, in the setting of acute MI, does not increase mean heart rate or the frequency of ventricular arrhythmias after MI. These data suggest that cardiac ACVt expression does not increase susceptibility to ventricular arrhythmias, unlike traditional sympathomimetic

TABLE 3. Propranolol Study

<table>
<thead>
<tr>
<th></th>
<th>Control (n)</th>
<th>ACVt (n)</th>
<th>Propranolol (n)</th>
<th>ACVt + Propranolol (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Survival</td>
<td>41 (34)</td>
<td>74 (34)</td>
<td>63 (19)*</td>
<td>78 (18)</td>
</tr>
<tr>
<td>Border apoptosis, (+nuc per 10^6 cells)</td>
<td>6719±1729 (7)</td>
<td>6495±2671 (7)</td>
<td>6254±1490 (5)</td>
<td>4868±1794 (5)</td>
</tr>
<tr>
<td>Remote apoptosis, (+nuc per 10^6 cells)</td>
<td>476±151 (7)</td>
<td>496±151 (7)</td>
<td>448±69 (5)</td>
<td>352±149 (5)</td>
</tr>
<tr>
<td>LVEF, %</td>
<td>17±5 (11)</td>
<td>25±6 (11)</td>
<td>19±6 (10)†</td>
<td>26±8 (11)</td>
</tr>
</tbody>
</table>

+nuc indicates positive (apoptotic) nuclei; LVEF, LV ejection fraction.

Data represent mean±SD. Number in parentheses indicates group size.

*P=0.44 vs ACVt; †P=0.09 vs ACVt.
interventions. Non-sustained ventricular tachycardia was frequently observed early after MI, but sustained ventricular tachycardia or ventricular fibrillation was not seen.

We found that the agonal rhythm consistently was bradycardia with progressive AV block. In clinical settings, MI of the large size that we induced in the present study (50% of LV) would be associated with severe heart failure. Bradycardia is commonly seen as a terminal rhythm in patients with severe heart failure. In murine models of myocardial ischemia/falction and in heart failure, very few instances of ventricular tachycardia or ventricular fibrillation have been documented, and the usual agonal rhythm is bradycardia.

We documented reduced mortality and reduced incidence of second- and third-degree AV block (P=0.02) in mice with cardiac-directed ACV1 expression. Recently, using electrophysiological approaches in transgenic mice, we found that cardiac-directed expression of ACV1 facilitated AV conduction through a wide range of heart rates. Increased cardiac ACV1 expression, by facilitating AV conduction, would be predicted to have a protective effect on fatal bradyarrhythmias associated with MI and is likely to have played a role in the mechanism for reduced mortality that we found in the present study.

ACV1 and propranolol had similar salutary effects on mortality and LV remodeling in the setting of acute MI. Those who assume that ACV1 gene transfer recapitulates βAR stimulation will think that these results are counterintuitive. However, given their unique roles as signaling molecules—one a βAR antagonist, the other an effector molecule for multiple G protein–coupled receptor pathways—one would not predict equal and opposite effects. Furthermore, βAR stimulation has effects on transcription and expression of key proteins important in cardiac function (eg, βAR, phospholamban, and atrial natriuretic factor) that are directionally opposite to those evoked by ACV1 gene transfer.

Clinical Implications

An American College of Cardiology/American Heart Association consensus panel recommends the use of βAR antagonists early in clinical acute MI, and clinical trials indicate that the use of βAR antagonists in this setting reduces mortality. Having established that increased cardiac content of ACV1 has an unanticipated favorable effect on survival in acute MI, we performed a secondary study to determine the effects of propranolol (versus ACV1) on mortality, LV function, and apoptosis rates in the present model. Propranolol had favorable effects on survival and LV function that were not statistically different from the effects of ACV1, and, like ACV1, propranolol did not alter apoptosis rates at this early time point after MI. The precise mechanism by which propranolol has a favorable effect on LV remodeling in clinical settings in the acute phase of MI is not known precisely, although favorable effects are associated with reduced apoptosis in longer-term studies. On the basis of the present data, we would anticipate that ACV1 gene transfer may have a beneficial effect on survival in acute MI in clinical settings. This effect of ACV1 does not negate and may even increase the beneficial effects of βAR blockade.

In conclusion, increased cardiac ACV1 content reduces mortality in acute MI without affecting infarct size. Three mechanisms contribute to this survival advantage: increased LV contractile responsiveness, reduced LV dilation, and reduced incidence of high-grade AV block. The molecular underpinning for favorable effects on LV function includes increased LV cAMP-generating capacity and calcium handling.

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Disclosures

None.

References


CLINICAL PERSPECTIVE

Clinical trials of cardiac gene transfer of adenylyl cyclase type VI (ACv6) for heart failure may soon be initiated. Increased cardiac ACv6 in transgenic mice results in structurally normal hearts with normal basal heart rate and function but supranormal responses to catecholamine stimulation. The use of β-adrenergic receptor (βAR)-stimulating agents, which increase intracellular cAMP, may cause sustained myocardial ischemia due to increased myocardial oxygen demand or may induce ventricular arrhythmias. Whether increased cardiac ACv6 has a deleterious effect on myocardial ischemia is unknown; however, increased cAMP generation and contractile force may be detrimental in the setting of myocardial infarction (MI) by increasing border zone injury and extending infarct size. In the present study, MI was induced by proximal left coronary ligation in transgenic mice with cardiac-directed expression of ACv6 and their transgene-negative littermates. We then assessed survival, infarct size, LV size and function, apoptosis rates, cAMP production, calcium handling, and incidence of arrhythmias. We found that increased ACv6 content reduces mortality in acute MI without affecting infarct size. Three mechanisms contribute to this survival advantage: increased LV contractile responsiveness, reduced LV dilation, and reduced incidence of high-grade AV block. The molecular underpinning for favorable effects on LV function includes increased LV cAMP-generating capacity and calcium handling. On the basis of the present data, we would anticipate that ACv6 gene transfer may have a beneficial effect on survival in acute MI in clinical settings. This effect of ACv6 does not negate and may even increase the beneficial effects of βAR blockade.
Increased Cardiac Adenylyl Cyclase Expression Is Associated With Increased Survival After Myocardial Infarction
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In the version of the article “Increased Cardiac Adenylyl Cyclase Expression Is Associated With Increased Survival After Myocardial Infarction” by Takahashi et al that published online before print on July 24, 2006, and appeared in the August 1, 2006, issue of the journal (Circulation. 2006;114:388–396), incorrect graphs were supplied for Figure 2B and 2C. The mistake did not change the results or conclusions of the article. The figure has been corrected in the current online version. The authors regret this error.

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