β-Adrenergic Receptor Blockers Restore Cardiac Calcium Release Channel (Ryanodine Receptor) Structure and Function in Heart Failure

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Background—β-Adrenergic receptor blockade is one of the most effective treatments for heart failure, a leading cause of mortality worldwide. The use of β-adrenergic receptor blockers in patients with heart failure is counterintuitive, however, because they are known to decrease contractility in normal hearts. The ryanodine receptor (RyR2) on cardiac sarcoplasmic reticulum is the key calcium release channel required for excitation-contraction coupling. In failing hearts, the stoichiometry and function of the RyR2 macromolecular complex is altered. Decreased levels of phosphatases (PP1 and PP2A) and hyperphosphorylation by protein kinase A result in dissociation of the regulatory protein FKBP12.6 and channels with increased open probability.

Methods and Results—Here, we show that systemic oral administration of a β-adrenergic receptor blocker reverses protein kinase A hyperphosphorylation of RyR2, restores the stoichiometry of the RyR2 macromolecular complex, and normalizes single-channel function in a canine model of heart failure.

Conclusions—These results may, in part, explain the improved cardiac function observed in heart failure patients treated with β-adrenergic receptor blockers. (Circulation. 2001;104:2843-2848.)

Key Words: heart failure ■ calcium ■ sarcoplasmic reticulum ■ ion channels ■ receptors, adrenergic, beta

Clinical trials have shown that β-adrenergic receptor blocker therapy results in a 20% to 66% reduction in mortality at 12 months in patients with heart failure (HF).1-3 It is not intuitively obvious, however, how β-adrenergic receptor blockers can improve cardiac function in failing hearts, because they are known to decrease contractility in normal hearts.4-6

HF is a complex disease7 that is characterized by a hyperadrenergic state.8 However, β-adrenergic receptors are downregulated and uncoupled from G proteins in failing hearts.9,10 Nevertheless, we recently showed that ryanodine receptor (RyR2) is protein kinase A (PKA)-hyperphosphorylated in HF,11 indicating that the net effect of β-adrenergic signaling is upregulated in HF with respect to RyR2 as a substrate for PKA phosphorylation. It is likely that the PKA hyperphosphorylation of RyR2 is a maladaptive response,12 because it results in the dephosphorylation of the regulatory subunit FKBP12.6,11,13 yielding channels that are pathologically sensitive to Ca2+-induced Ca2+ release from the sarcoplasmic reticulum (SR).11 RyR2 is a macromolecular complex that includes FKBP12.6 as well as PKA and 2 phosphatases (PP1 and PP2A) that are bound to the cytoplasmic domain of the channel via targeting proteins.11,14 In failing hearts, the RyR2 macromolecular complex undergoes remodeling characterized by a reduction in the amounts of PP1, PP2A, and FKBP12.6 that are bound to the cytoplasmic domain of the channel.11

In the present study, we used a well-characterized canine model of pacing-induced HF to show that β-adrenergic receptor blockade both restores the normal stoichiometry of the RyR2 macromolecular complex and normalizes the function of the channel.

Methods

HF Model

Seventeen dogs weighing 28 to 30 kg were used for the study. A rapid cardiac pacing regimen that results in severe HF was used as described previously.15 Animals were assigned to 1 of 4 groups: (1) normal without heart instrumentation (n=6), (2) HF (n=10), (3) HF treated with metoprolol (n=6), and (4) normal without heart instrumentation plus metoprolol (n=2). In groups 2 and 3, after baseline measurements had been obtained, rapid left ventricular (LV) pacing was initiated at 210 bpm for 3 weeks, followed by an additional week of pacing at 240 bpm with an external pacemaker (EV4543, Pace...
Medical, Inc.). Metoprolol (25 mg PO BID, Mylan Pharmaceuticals Inc) was begun 2 weeks after initiation of pacing and continued for 2 weeks. Metoprolol was begun 2 weeks after baseline measurement for the control dogs with heart instrumentation. Hemodynamic assessment was performed at baseline and at 2, 3, and 4 weeks. Hemodynamic measurements were performed ≥40 minutes after the pacemaker was turned off. Baseline LV change in pressure over time (dp/dtmax, mm Hg/s) was 344 ± 117 (n=24) and fell to 1730 ± 304 (n=10, P<0.01) in animals subjected to rapid LV pacing, consistent with the development of HF. Because rapid LV pacing was continued throughout the metoprolol treatment period, this model was not designed to assess whether β1-adrenergic receptor blockade restores normal hemodynamic function in failing hearts. It has previously been demonstrated, however, that β1-adrenergic receptor blockade, including therapy with metoprolol, improves LV function in heart in both humans and dogs16,17 and improves survival.2

**Ryanodine Receptor Macromolecular Complex**

SR membranes were prepared from canine ventricular tissue as described previously.11,18 Protein concentration was measured by Bradford assay. SR samples were stored at −80°C until use. Cardiac homogenates were prepared with 1.0 g of cardiac tissue homogenized in 1.0 mL of a buffer [mmol/L: Tris-HCl 50 (pH 7.4), NaCl 200, NaF 20, NaVO3 1.0, and DTT 1.0], and protease inhibitors. Samples were centrifuged at 3000 g for 10 minutes and stored at −80°C until use.

Cardiac homogenates (500 μg) were suspended in 0.5 mL of modified RIPA buffer [50 mmol/L Tris-HCl (pH 7.4), 0.9% NaCl, 1.0 mmol/L NaF, 1.0 mmol/L Na3VO4, 0.25% Triton X100, and protease inhibitors]. Samples were incubated with anti-RyR (5029) antibody overnight at 4°C. Protein A sepharose beads were added, incubated at 4°C for 1 hour, washed with 1× phosphorylation buffer [8 mmol/L MgCl2, 10 mmol/L EGTA, and 50 mmol/L Tris/piperazine-N,N'-bis-(2-ethanesulfonic acid), pH 6.8], and resuspended in 10 μL of a 1.5× phosphorylation buffer containing either vehicle alone, PKA catalytic subunit (Sigma), or PKA plus a PKA inhibitor (PKI, 5 μmol/L, Calbiochem). Backphosphorylation of immunoprecipitated RyR2 was initiated with 33 μmol/L of ATP (NEN Life Sciences) and terminated after 5 minutes at room temperature with 5 μL of stop solution (4% SDS and 0.25 mol/L DTT). Samples were size-fractionated on 6% SDS-PAGE, and RyR2 radioactivity was quantified with a Molecular Dynamics PhosphorImager and ImageQuant software (Amer sham Pharmacia Biotech). Nonspecific phosphorylation (not inhibited by PKA inhibitor) was subtracted, and the resulting value was divided by the amount of RyR2 protein (determined by immunoblotting and densitometry) and expressed as the inverse of the specific PKA-dependent [γ-32P]ATP signal.

Cardiac homogenates were immunoprecipitated with anti-RyR antibody, and samples were size-fractionated with SDS-PAGE and immunoblotted as previously described.11 Primary antibodies used were anti-PKA catalytic subunit 1:1000, anti-PP1 1:1000, and anti-RII A and B 1:1000 from Transduction Laboratories; anti-PKA catalytic subunit 1:1000, anti-PP1 1:1000, anti-PP2A 1:1000 from New England Biolabs; and anti-RyR (5029, 1:3000). Data shown represent results from 3 or more separate experiments.

β-Adrenergic receptor binding studies were performed as previously described20: adrenergic receptor density and affinity were reduced in the failing hearts (normal hearts: Bmax = 36.5 ± 0.9 fmol/mg, Kd = 4.3 ± 0.3 nmol/L versus failing hearts: Bmax = 29.7 ± 0.3 fmol/mg, Kd = 10.0 ± 0.8 nmol/L, n=6, P<0.01), and both were restored to normal with metoprolol (Bmax = 34.9 ± 2.1 fmol/mg, Kd = 6.2 ± 1.7 nmol/L, n=6, P<0.01 compared with failing hearts, P=NS compared with normal hearts).

**Single-Channel Recordings**

Single-channel recordings of RyR2 were performed and analyzed under voltage-clamp conditions as described previously.11 Solutions used for channel analysis were (mmol/L): trans solution, HEPES 250 and Ca(OH)2 53, pH 7.35, and cis solution, HEPES 250, Tris 125, EGTA 1, and CaCl2 0.5, pH 7.35. Free [Ca2+] (cis) 150 mmol/L was calculated by use of Chelator software.21 At the conclusion of each experiment, ryanodine or ruthenium red was applied to confirm the identity of channels as RyR2. Results are presented as mean±SD; Student’s t test or ANOVA (where indicated) was used for statistical analyses.

**Results**

HF was induced by rapid LV pacing and verified by hemodynamic measurements showing a significant increase in LV end-diastolic pressure from 5.4±2.5 to 23.1±4.8 mm Hg (n=10, P<0.01). After the establishment of HF, animals were treated with the β1-adrenergic receptor blocker metoprolol (25 mg PO BID), a dose that is comparable to or less than that used in patients16 with HF.

As we previously reported,11 RyR2 was PKA-hyperphosphorylated in failing hearts (Figure 1). PKA phosphorylation of immunoprecipitated RyR2 was assessed with backphosphorylation as previously described.11 Metoprolol treatment reversed the PKA hyperphosphorylation of RyR2 in failing hearts, returning the channel phosphorylation to the levels seen in normal nonfailing hearts (Figure 1). Because there is a single site on each RyR2 molecule (serine 2809) that is PKA-phosphorylated in vivo, there are 4 per tetrameric channel.11 The stoichiometry of PKA backphosphorylation of RyR2, determined as previously described,11 was 3.18±0.91 moles of phosphate transferred per mole of channel from normal hearts (n=6), compared with 0.72±0.13 moles of phosphate transferred per mole of channel from failing hearts (n=10, P<0.01 compared with normal hearts by ANOVA) and 2.94±0.15 moles of phosphate transferred per mole of channel (n=6, P=NS compared with normal hearts by ANOVA) from failing hearts in animals treated with metoprolol. These data indicate that in failing hearts, ~3 of 4 PKA sites on the tetrameric RyR2 were PKA-phosphorylated in vivo, whereas only 1 of these sites was PKA-phosphorylated in RyR2 from normal hearts and in failing hearts in animals.
We have previously shown that PKA hyperphosphorylation of RyR2 in failing hearts dissociates the channel regulatory protein FKBP12.6 from RyR2, resulting in defective channel function characterized by increased open probability \( (P_o) \) and increased gating frequency \( (f_o) \). A significant \( (P<0.01 \text{ by ANOVA}) \) decrease in the amount of PP1, PP2A, and FKBP12.6 was associated with RyR2 in failing hearts compared with normal hearts (Figure 2A through 2F). Metoprolol treatment of HF animals restored the level of FKBP12.6 bound to RyR2 to normal (Figure 2F); there is no change in the total amount of FKBP12.6 in failing versus normal hearts.\(^{11}\) Like FKBP12, which stabilizes skeletal muscle RyR1 function\(^ {19,23,24}\) and is required for coupled gating between individual channels,\(^ {25}\) FKBP12.6 plays a similar role in the RyR2 macromolecular complex.\(^ {11,18,26}\)

To determine whether the \( \beta \)-adrenergic blockade–induced normalization of PKA phosphorylation of RyR2 and restoration of the stoichiometry of the macromolecular complex was associated with normalization of channel function, we examined the single-channel properties of RyR2 in planar lipid bilayers as previously described.\(^ {11}\) One hundred fifty-three RyR2 channels were studied, including 55 channels from 4 nonfailing canine hearts (Figure 3A), 55 channels from 5 failing canine hearts (Figure 3B), and 43 channels from 4 failing hearts from animals treated with metoprolol (Figure 3C). Compared with RyR2 from normal hearts, RyR2 channels from failing hearts exhibited significantly increased \( P_o \) and/or \( f_o \) \((\text{Table and Figure 3A, compared with Figure 3B}).\) Both increased \( P_o \) and increased \( f_o \) are seen when FKBP12.6 is removed from RyR2.\(^ {11,18}\) Compared with channels from normal hearts, in which 0 of 55 channels exhibited increased \( P_o \) and/or \( f_o \) \((\text{Table and Figure 3B}).\) In contrast, only 12% of the RyR2 channels \((5/43, P<0.01)\) from failing hearts from animals treated with metoprolol were abnormal \((\text{Table}).\) Although 93% of the RyR2 channels from failing hearts exhibited abnormal function in planar lipid bilayers, as previously reported,\(^ {11}\) the single-channel properties were heterogeneous \((\text{Table and Figure 3B}).\) This heterogeneity may reflect the fact that each individual channel may have anywhere from 0 to 4 of the 4 possible serines phosphorylated and may have anywhere from 0 to 4 molecules of FKBP12.6 bound to the channel. The single-channel properties of RyR2 from failing hearts would be expected to be heterogeneous, with only a subset of channels exhibiting the most severe defects. If all of the RyR2 channels from failing hearts had increased \( P_o \) at low \( \text{cis} \) (cytosolic \( \text{Ca}^{2+} \)), this would be incompatible with life. To assess the heterogeneous function of RyR2 from failing hearts, the channels were segregated into 3 clearly distinguishable functional groups (Table). Group A includes channels with normal \( P_o \) and \( f_o \) \((\text{Table and Figure 3B}).\) Group B includes channels with normal \( P_o \) and increased \( f_o \) \((\text{Table and Figure 3B}).\) Group C includes channels with increased \( P_o \) and \( f_o \) \((\text{Table and Figure 3B}).\) Thus, group C includes channels with the most severe functional defects. There were no channels from normal hearts in groups B or C, whereas 93% of the channels from failing hearts were in groups B or C, with 45% in group C. Of the channels from HF treated with \( \beta \)-blockers, 12% were in groups B or C but only 6% were in group C. This heteroge-

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**Figure 2.** \( \beta \)-Adrenergic receptor blockade normalizes levels of proteins in RyR2 macromolecular complex. Heart homogenates were immunoprecipitated with anti-RyR antibody as described.\(^ {11}\) Representative immunoblots are shown for each component of RyR2 macromolecular complex: (A) RyR2, (B) PKA, (C) RII, (D) PP2A, (E) PP1, and (F) FKBP12.6 \((\text{Figure 2D})\). The amount of each component of the RyR2 macromolecular complex was determined by densitometry of immunoblots. Results are relative to RyR2 levels. Error bars are SD.

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nect in the function of RyR2 channels from failing hearts is consistent with our previous observation that 
70% of the channels exhibited abnormal single-channel properties, including 56% that exhibited some increase in $P_o$ at low cis (cytosolic, 150 nmol/L) Ca$^{2+}$ and 15% that exhibited a large increase in $P_o$ at 50 nmol/L cis (cytosolic) Ca$^{2+}$.

**Discussion**

Taken together, these data indicate that systemic $\beta$-adrenergic blockade can reverse the defects in the structure and function of RyR2 observed in failing hearts. Regulation of Ca$^{2+}$ homeostasis in cardiomyocytes is a complex process that requires the integrated function of multiple Ca$^{2+}$-handling systems.

**Single-Channel Properties of RyR2 From Normal Hearts, Failing Hearts, and Failing Hearts From Animals Treated With $\beta$-Adrenergic Receptor Blockers (Metoprolol)**

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Heart Failure</th>
<th>Heart Failure + $\beta$-Blockers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. of channels</td>
<td>A (55)</td>
<td>B (4)</td>
</tr>
<tr>
<td>$P_o$, 0.01</td>
<td>0.01±0.01</td>
<td>0.02±0.02</td>
<td>0.06±0.16</td>
</tr>
<tr>
<td>$f_o$, s$^{-1}$</td>
<td>0.61±0.59</td>
<td>0.58±0.68</td>
<td>15.98±9.63*</td>
</tr>
</tbody>
</table>

RyR2 channels from failing hearts and failing hearts from animals treated with metoprolol were segregated into 3 distinct groups: group A includes channels with normal $P_o$ and $f_o$, group B includes channels with normal $P_o$ and increased $f_o$, and group C includes channels with increased $P_o$ and $f_o$. See text for explanation of groups A, B, and C.

$^*P<0.01$ vs channels from normal hearts.
molecules.\textsuperscript{27} RyR2 plays a key role in cardiac excitation-contraction coupling, and data from our laboratory and others suggest that dysregulation of SR Ca\textsuperscript{2+} release via RyR2 could contribute to defects in Ca\textsuperscript{2+} signaling in failing hearts.\textsuperscript{11,28–35} Many studies have shown that \textbeta-\textadrenergic blockade can restore function in failing hearts.\textsuperscript{17,30,36–39} We have proposed that hyperphosphorylated RyR2 depleted of FKBP12.6 could contribute to a reduction in SR Ca\textsuperscript{2+} content and uncoupling of RyR2.\textsuperscript{26} The chronic alterations in RyR2 function could contribute to a reduction in excitation-contraction coupling gain and decreased Ca\textsuperscript{2+} transients in failing hearts and possibly produce diastolic Ca\textsuperscript{2+} release that can trigger delayed afterdepolarizations\textsuperscript{40} and initiate fatal ventricular arrhythmias (sudden cardiac death).\textsuperscript{11,12} In agreement with these possibilities, recent studies have shown either a reduction in SR Ca\textsuperscript{2+} content,\textsuperscript{41} decreased Ca\textsuperscript{2+} transients,\textsuperscript{42} or decreased excitation-contraction coupling gain\textsuperscript{43} in cardiomyocytes from failing hearts as well as reduced levels of FKBP12.6 in the RyR2 macromolecular complex.\textsuperscript{44}

Systemic \textbeta-\textadrenergic receptor blockade therapy has multiple effects on a wide range of signaling molecules both in the heart and in other tissues. The present study focuses on one of these pathways and demonstrates normalization of RyR2 structure and function in failing hearts treated with \textbeta-\textadrenergic receptor blockade. RyR2 is one of the first molecular targets identified for \textbeta-\textadrenergic receptor blockade therapy outside of the \textbeta-\textadrenergic receptor signaling pathway. The restoration of normal RyR2 structure and function contributes to a mechanistic understanding that may in part explain some of the beneficial effects of \textbeta-\textadrenergic receptor blockade observed in HF.

Acknowledgments
This study was supported by grants to Dr Marks from the National Institutes of Health, the American Heart Association, and the Richard and Lynne Kaiser Family Foundation and to Dr Reiken from the Whitaker Foundation. Dr Marks is a Doris Duke Foundation Distinguished Clinical Scientist. We thank members of the Marks laboratory for helpful discussions and comments on the manuscript.

References


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_Circulation_. 2001;104:2843-2848
doi: 10.1161/hc4701.099578

_Circulation_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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