Reduced effects of BAY K 8644 on L-type Ca\textsuperscript{2+} current in failing human cardiac myocytes are related to abnormal adrenergic regulation

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Reduced effects of BAY K 8644 on L-type Ca\textsuperscript{2+} current in failing heart with a left ventricular assist device (LVAD) improves contractility and adrenergic responses, we further hypothesized that BAY K effects on \( I_{\text{Ca,L}} \) would be restored in LVAD-supported failing hearts. We tested our hypotheses in human ventricular myocytes (HVMs) isolated from nonfailing (NF), failing (F), and LVAD-supported failing hearts. We found that \( I_{\text{Ca,L}} \) was diminished in F HVMs compared with NF HVMs; 2) BAY K had smaller effects on \( I_{\text{Ca,L}} \) in NF HVMs pretreated with isoproterenol (Iso) or dibutyryl cyclic AMP (dBcAMP); 3) BAY K effects on \( I_{\text{Ca,L}} \) in F HVMs pretreated with acetylcholine (Ach) were normalized; 4) Iso had no effect on NF HVMs pretreated with BAY K; 5) BAY K effects on \( I_{\text{Ca,L}} \) in LVAD HVMs were similar to those in NF HVMs; 6) BAY K effects were reduced in LVAD HVMs pretreated with Iso or dBcAMP; 7) Iso had no effect on \( I_{\text{Ca,L}} \) in LVAD HVMs pretreated with BAY K. Collectively, these results suggest that the decreased BAY K effects on LTCC in F HVMs are caused by increased basal channel activity, which should contribute to abnormal contractility reserve.

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that increased basal activity levels of the LTCC, possibly due to increased phosphorylation state, may cause decreased responses to BAY K in F HVMs. These experiments also addressed whether or not adrenergic agonists and BAY K have independent (31, 42) or interactive (16, 43) effects on the LTCC. Our experiments show that the effects of both BAY K and Iso on LTCCs are smaller in F HVMs than in HVMs from nonfailing (NF) and LVAD-supported hearts. Exposure to high catecholamines in failing hearts.

### MATERIALS AND METHODS

**Isolation of HVMs and I_{CaL} recording.** HVMs were isolated from 7 nonfailing (NF), 15 failing (F), and 14 LVAD-supported failing human hearts as described previously (8). Failing and LVAD-supported failing human hearts were obtained from the Temple Cardiac Transplant Team at the time of cardiac transplantation. Nonfailing hearts were donor hearts unsuitable for transplantation. Our protocol was approved by Temple University Institutional Review Board. Patient characteristics are presented in Table 1. Isolated HVMs were used within 12 h postisolation.

The L-type Ca^{2+} current (I_{CaL}) was measured in a sodium-free and potassium-free solution as described previously (8). In short, isolated myocytes were placed in a chamber mounted on an inverted microscope (Nikon Diaphot) and perfused with normal Tyrode solution (composition in mM: 10 glucose, 5 HEPES, 5.4 KCl, 1.2 MgCl_2, 150 NaCl, and 2 Na-pyruvate, pH 7.4 with NaOH). Both the inflow solution and the chamber were water-heated to maintain the temperature at 36 ± 1°C. A 1–4 MΩ pipette filled with a Cs+-containing solution [composition in mM: 130 Cs-aspartate, 10 N-methyl-D-glucamine (NMDG), 20 tetraethylammonium chloride, 10 HEPES, 2.5 Tris-ATP, 1 MgCl_2, and 10 EGTA, pH 7.2, and drugs needed specifically for experiments] was used to obtain gigaseals. Once a gigaseal was formed, the patch was ruptured and the cell was dialyzed for 10 min. The extracellular bath was then changed to a Ca^{2+}-substitution bath solution (composition in mM: 2.4-aminopyridine, 2 CaCl_2, 5.4 CsCl, 10 glucose, 5 HEPES, 1.2 MgCl_2, and 150 NMDG, pH 7.4 with CsOH). Membrane voltage was controlled by an Axopatch 2B voltage-clamp amplifier and digitized by Digidata 1200 using pClamp8 software ( Molecular Devices). Once the signal was digitized, the patch was ruptured and the cell was dialyzed

For the experiments testing drug effects, myocytes were exposed to drugs and the effects were monitored by recording I_{CaL} at +10 mV from the holding potential of ~70 mV every 20 s. When effects were stable, the I_{CaL}-voltage relationship was again determined. Only myocytes with minimal (~10%) rundown of I_{CaL} were included in the data sets. Whole cell LTCC conductance (G) was calculated by dividing the I_{CaL} density by the driving force for Ca^{2+} ions (V_{test} – V_{rev}), where V_{test} is the test potential and V_{rev} is the apparent reversible potential.

**Statistics.** Data are means ± SE. Paired or unpaired t-tests were used to evaluate statistics on single-factor two-group comparison. Differences among multiple groups were tested with ANOVA or repeated-measures ANOVA with SAS (SAS Institute). A P value of 0.05 was considered significant. N indicates how many hearts were used, and n is the number of cells measured.

### RESULTS

**Effects of BAY K 8644 on I_{CaL} in NF and F HVMs.** Inotropic effects of BAY K are smaller in failing versus normal myocytes (1, 34, 39). To explore the underlying mechanism, we measured the effects of BAY K on I_{CaL} in NF (n = 16, N = 4) and F HVMs (n = 24, N = 6). I_{CaL} density, current-voltage relationship (I-V), voltage-dependent activation (G-V), and fast (τ_f) and slow (τ_s) time constants of I_{CaL} decay were measured. BAY K increased I_{CaL} density, shifted the I-V relationship and G-V, and enhanced I_{CaL} decay (Fig. 1). The maximal I_{CaL} density, shifted the I-V relationship and G-V, and enhanced I_{CaL} decay were measured. BAY K caused the leftward shift of G-V curves in NF (V_0.5: basal, 0.43 ± 1.95 mV; BAY K, −8.94 ± 1.80 mV; P < 0.001) and F HVMs (basal: −7.96 ± 0.99 pA/pF; BAY K: −15.78 ± 1.39 pA/pF; P < 0.001) and F HVMs (basal: −8.05 ± 0.43 pA/pF; BAY K: −12.38 ± 0.56 pA/pF; P < 0.001).

### Table 1. Patient characteristics

<table>
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<th>Patient</th>
<th>Etiology</th>
<th>Duration of LVAD, days</th>
<th>Age, yr</th>
<th>CHF Duration, mo</th>
<th>LVEF, %</th>
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<td>NF (N = 7)</td>
<td>Idiopathic (3), ischemic (10), hypertension (1), valvular (1)</td>
<td>59±8</td>
<td>0</td>
<td>54.0±2.6</td>
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<tr>
<td>F (N = 15)</td>
<td>Idiopathic (2), ischemic (10), hypertension (1), valvular (1)</td>
<td>54±3</td>
<td>70±14</td>
<td>12.2±1.3</td>
<td></td>
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<tr>
<td>LVAD (N = 14)</td>
<td>Idiopathic (4), ischemic (8), hypertension (1), dilated (1)</td>
<td>164±53</td>
<td>53±3</td>
<td>51±9</td>
<td>12.5±0.7</td>
</tr>
</tbody>
</table>

Values are means ± SE. LVAD, left ventricular assist device; CHF, congestive heart failure; LVEF, left ventricular ejection fraction; NF, nonfailing heart; F, failing heart.
Figure 1. Effects of BAY K 8644 (BAY K) on L-type Ca\(^{2+}\) current (\(I_{\text{CaL}}\)) in nonfailing (NF; \(n = 16\) cells, \(N = 4\) hearts) and failing (F; \(n = 24\) cells, \(N = 6\) hearts) human ventricular myocytes (HVMs). A and E: representative recordings of \(I_{\text{CaL}}\) under control conditions and after application of BAY K in NF (A) and F HVMs (E). B and F: current-voltage (\(I-V\)) relationships in NF and F HVMs before (basal) and after BAY K. BAY K increased maximal \(I_{\text{CaL}}\) densities significantly in both NF and F HVMs, but its effect was smaller in F HVMs (%increase in maximal \(I_{\text{CaL}}\): NF, 96 ± 12%; F, 59 ± 8%). C and G: voltage dependence of activation (\(G_{\text{Ca}}/G_{\text{Ca, max}}\)) curves fitted with Boltzmann equations in NF and F HVMs under control conditions and after application of BAY K. BAY K caused a leftward shift of voltage-dependent activation curves in NF and F HVMs. This shift was more obvious in NF myocytes. After BAY K, half-maximal activation voltage (\(V_{0.5}\)) values in NF and F myocytes were not different (\(P = 0.73\)). D and H: effects of BAY K on fast (\(\tau_f\)) time constants at different test potentials in NF and F HVMs. BAY K significantly decreased \(\tau_f\), suggesting the acceleration of \(I_{\text{CaL}}\) decay. #\(P < 0.05\); $\#P < 0.001$; @\(P < 0.0001\) at the corresponding test potential. Bonferroni post hoc tests were done to compare the values at each test potential after 2-way repeated ANOVA test showed that drug had significant effects on \(I_{\text{CaL}}\).

Effects of BAY K 8644 on \(I_{\text{CaL}}\) in NF HVMs Pretreated with Iso

\(I_{\text{CaL}}\) in F HVMs is less responsive to Iso stimulation than in normal myocytes, possibly due to higher basal phosphorylation state and increased open probability of the LTCC (8). We tested BAY K effects on the LTCC in NF HVMs pretreated with 1 \(\mu\)M Iso to explore this idea. BAY K had smaller effects on \(I_{\text{CaL}}\) after Iso treatment (basal: \(-10.3 ± 1.7\) pA/pF; Iso: \(-15.0 ± 1.9\) pA/pF; Iso + BAY K: \(-18.3 ± 1.5\) pA/pF; \(n = 10\), \(N = 4\); \(P < 0.01\), Iso vs. basal; \(P < 0.001\), BAY K + Iso vs. basal; \(P < 0.05\), BAY K + Iso vs. Iso; one-way repeated ANOVA with post hoc tests, Fig. 2, A and B). The percent increase in \(I_{\text{CaL}}\) upon BAY K stimulation in Iso-pretreated NF HVMs was significantly less (\(F\)-test, \(P \approx 0.05\)) than in NF HVMs not pretreated with Iso (53 ± 10 vs. 96 ± 12%) and was similar to the increase of \(I_{\text{CaL}}\) in F HVMs induced by BAY K. BAY K significantly shifted the \(V_{0.5}\) of \(I_{\text{CaL}}\) activation in Iso-pretreated NF HVMs (\(V_{0.5}\): basal, \(0.75 ± 1.65\) mV; Iso, \(-4.90 ± 3.21\) mV; Iso + BAY K, \(-9.85 ± 1.85\) mV; \(P < 0.05\), basal vs. Iso; \(P < 0.05\), Iso + BAY K vs. Iso), but the change produced by BAY K after Iso pretreatment was less than with BAY K alone. The \(V_{0.5}\) after Iso + BAY K was not different from the \(V_{0.5}\) of NF HVMs treated with BAY K alone.

Stimulation and decreased phosphatase activity in the failing heart (41). We tested this idea further by measuring the effects of BAY K on the LTCC after exposure to adrenergic agonists in NF and F HVMs.

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HIGH PHOSPHORYLATION REDUCES BAY K EFFECT ON LTCCs IN FAILING MYOCYTES

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0.0001) and F HVMs (\(V_{0.5}\): basal, \(-1.78 ± 1.80\) mV; BAY K, \(-6.65 ± 2.08\) mV; \(P < 0.001\)). This shift was greater in NF myocytes (Fig. 1). The change of the \(V_{0.5}\) for LTCC activation induced by BAY K in NF (\(\Delta V_{0.5}\): \(-9.25 ± 1.30\) mV) myocytes was significantly larger than in F myocytes (\(\Delta V_{0.5}\): \(-4.87 ± 1.26\) mV). The \(V_{0.5}\) was not different among groups after BAY K (\(P = 0.73\)). Therefore, the difference in BAY K effects on \(V_{0.5}\) in F compared with NF HVMs results from the fact that \(V_{0.5}\) is already shifted leftward in F myocytes. Phosphorylation of the LTCC is known to induce a leftward shift of LTCC activation (8, 41). Therefore, this result is consistent with the hypothesis that the basal phosphorylation state of the LTCC is increased in the failing human heart.

BAY K also increased the rate of \(I_{\text{CaL}}\) decay (Fig. 1, D and H). When \(I_{\text{CaL}}\) decay was fit with a double-exponential decay relationship, we found that \(\tau_f\) (Fig. 1, D and H), but not \(\tau_s\) (data not shown) was decreased by BAY K (10). Sanguinetti et al. (40) previously reported that BAY K decreased both \(\tau_f\) and \(\tau_s\) of the \(I_{\text{CaL}}\). This acceleration of the decay of \(I_{\text{CaL}}\) by BAY K could be due to enhanced Ca\(^{2+}\)-dependent inactivation (32) and/or direct effects of BAY K on channel gating (40).

The results showing that BAY K increased the amplitude, shifted the \(G-V\) curves, and accelerated the decay of \(I_{\text{CaL}}\) in NF and F HVMs are consistent with previous studies in normal myocytes (33). However, the bases of the diminished effects of BAY K on \(I_{\text{CaL}}\) in failing myocytes are not clear. Our hypothesis is that the reduced effect of BAY K on \(I_{\text{CaL}}\) in F HVMs is due to an increased activity of the LTCC, possibly due to increased phosphorylation resulting from enhanced adrenergic
Fig. 2. Effects of BAY K on I_{CaL} of NF HVMs pretreated with Isoproterenol (Iso; n = 10 cells, N = 4 hearts). A: representative recordings of I_{CaL} in basal conditions, with Iso, and with both Iso and BAY K. B: I-V relationships before (basal) and after application of Iso and Iso + BAY K. Iso significantly (P < 0.05, ANOVA) increased maximal I_{CaL} by 64 ± 18% (basal: −10.3 ± 1.7 pA/pF; Iso: −15.0 ± 1.9 pA/pF), and combined Iso with BAY K further increased maximal I_{CaL} by 53 ± 10% (−18.3 ± 1.5 pA/pF); after Iso-induced a leftward shift of the activation curve, BAY K further shifted the voltage dependence of activation. The change produced by BAY K after Iso pretreatment was less than that by BAY K alone on NF HVMs (V_{0.5}: basal, 0.75 ± 1.65 mV; Iso, −4.90 ± 3.21 mV; Iso + BAY K, −9.85 ± 1.85 mV; P < 0.05, vs. basal; P < 0.05, Iso + BAY K vs. Iso) (see Fig. 1). C: τ_{a} of I_{CaL} decay at basal level, pretreatment (Iso), and combined treatment (BAY K + Iso) in NF HVMs. Iso decreased τ_{a} at most test potentials, and BAY K + Iso further decreased τ_{a}. **P < 0.05, basal vs. Iso; ***P < 0.01, basal vs. Iso; #P < 0.05, Iso vs. BAY K + Iso; @P < 0.05, basal vs. Iso + BAY K; @@P < 0.01, basal vs. Iso + BAY K.

Effects of BAY K 86444 on I_{CaL} in NF and F HVMs pretreated with pipette DBcAMP. Adrenergic signaling is abnormal in F HVMs (38) and could be altered in our NF HVMs because they were primarily from old donors (49) (see Table 1 for average age). Therefore, a nonhydrolyzable DBcAMP (in pipette solution) was used to directly activate PKA and enhance LTCC activity. BAY K effects on these activated LTCCs were then tested. Ten minutes of cell dialysis was needed for DBcAMP to have stable, maximal effects, and then BAY K was administered via the perfusion solution. Depolarizing steps to +10 mV at 0.05 Hz were utilized to monitor DBcAMP and BAY K effects on I_{CaL}. DBcAMP significantly increased the peak I_{CaL} density in 12 F HVMs from 5 failing human hearts (−18.0 ± 2.5 pA/pF) and in 9 NF HVMs (−24.8 ± 1.8 pA/pF, N = 3) (Fig. 3B). The peak I_{CaL} density after DBcAMP was significantly smaller in F HVMs than in NF HVMs. DBcAMP shifted the activation of I_{CaL} in both NF and F HVMs, and after DBcAMP treatment, there was no more difference in the activation voltage dependence between NF and F HVMs, as we reported previously (8). In a subset of these F and NF HVMs, we successfully tested BAY K effects on I_{CaL} after DBcAMP exposure. BAY K did not significantly increase maximal I_{CaL} density in NF or F HVMs pretreated with DBcAMP ([DBcAMP + BAY K]/[DBcAMP]: 111.9 ± 9.8% in NF, n = 5, N = 2, vs. 121.0 ± 11.2% in F, n = 6, N = 2] (Fig. 3, A, E, and F). BAY K significantly shifted the V_{0.5} of I_{CaL} activation in NF ([DBcAMP + BAY K]/DBcAMP: −9.2 ± 1.5 mV; DBcAMP + BAY K, −13.3 ± 1.6 mV; P < 0.05) and F HVMs ([DBcAMP + BAY K]/DBcAMP: −9.2 ± 1.4 mV; DBcAMP + BAY K, −15.8 ± 2.9 mV; P < 0.05) pretreated with DBcAMP to more negative voltages. However, as in NF HVMs pretreated with Iso (Fig. 1C), the change in V_{0.5} was significantly smaller than the change in V_{0.5} induced by BAY K in the absence of Iso.

Tiaho et al. (43) showed slowing of I_{CaL} decay after BAY K when cAMP was in the pipette solution. We only observed this effect in one of five NF HVMs and one of six F HVMs tested (Fig. 3, D and H). This difference could be due to the fact that we performed our studies in human myocytes and/or that enhanced Ca^{2+}-dependent inactivation disguises a direct effect of BAY K to slow of I_{CaL} decay.

Effects of Iso on I_{CaL} in NF HVMs pretreated with BAY K. Our results show that after adrenergic stimulation, BAY K has reduced effects on the LTCC, consistent with a common mechanism of action. We tested whether or not BAY K exposure also reduces the stimulatory effects of adrenergic agonists on the LTCC. In NF HVMs (n = 7, N = 3), after exposure to BAY K, the LTCC did not respond further to Iso (Fig. 4, A and C). After BAY K, Iso had no significant effects on I_{CaL} amplitude (maximal I_{CaL}: basal, −8.9 ± 2.1 pA/pF; BAY K, −15.3 ± 2.3 pA/pF; Iso + BAY K, −20.6 ± 3.5; P < 0.05, basal vs. BAY K; P > 0.05, BAY K vs. Iso + BAY K; one-way repeated ANOVA). Iso did not shift the G-V curve further in NF HVMs pretreated with BAY K (V_{0.5}: basal, −1.0 ± 2.6 mV; BAY K, −7.7 ± 3.1 mV; Iso + BAY K, −10.8 ± 4.5 mV; P < 0.05, basal vs. BAY K; P > 0.05, Iso +
BAY K vs. BAY K; one-way repeated ANOVA, \( n = 7, N = 3 \) (Fig. 4D). These results are not in agreement with the additive effects of BAY K and Iso found by Markevich et al. (31) and Sculptoreanu et al. (42). Conversely, our results support the idea that the effects of adrenergic agonists and BAY K on the LTCC are through a common mechanism.

Effects of BAY K on \( I_{CaL} \) in F HVMs pretreated with ACh. An increased basal phosphorylation state of the LTCC in heart failure would increase channel activity and shift the voltage-dependent activation. These effects could account for the diminished effects of BAY K on \( I_{CaL} \) in F HVMs (8). In this scenario, BAY K effects should be at least partially restored after dephosphorylation of the LTCC. We tested this idea by exposing F HVMs to 20 \( \mu \)M ACh, which should dephosphorylate the LTCC (31). ACh decreased maximal \( I_{CaL} \) by 27.4 \( \pm \) 4.8% in F HVMs, and subsequently, BAY K increased \( I_{CaL} \) by 101.0 \( \pm \) 15.7% (maximal \( I_{CaL} \): basal, 8.9 \( \pm \) 1.3 pA/pF; ACh, 6.3 \( \pm \) 0.5 pA/pF; ACh + BAY K, 12.3 \( \pm \) 0.6 pA/pF; \( P < 0.05 \) at the same voltage. Db, DBcAMP.

Fig. 4. Effects of Iso on \( I_{CaL} \) in NF HVMs pretreated with BAY K (\( n = 7, N = 3 \) hearts). A: representative recordings of maximal \( I_{CaL} \) under basal conditions, with BAY K, and then with a combination of Iso and BAY K. B: \( \tau_i \) at different test potentials under control conditions, with BAY K, and with BAY K + Iso. BAY K significantly enhanced \( I_{CaL} \) decay, but combined BAY K + Iso did not significantly slow down the decay of \( I_{CaL} \). C: BAY K significantly increased the maximal \( I_{CaL} \) in NF HVMs (122 \( \pm \) 43%), and further application of Iso had no significant effect. D: BAY K significantly shifted the activation curve to the left, and further application of Iso did not significantly shift the activation curve. \# \( P < 0.05 \), basal vs. BAY K; ^* \( P < 0.05 \), basal vs. BAY K + Iso; ^@ \( P < 0.01 \), basal vs. BAY K + Iso.
0.05, basal vs. ACh; \( P < 0.05 \), ACh vs. ACh + BAY K, \( n = 5 \), \( N = 2 \) (Fig. 5, A–C). Effects of BAY K after ACh in F HVMS were comparable to the effects of BAY K on NF cells without any treatment. ACh did not alter \( V_{0.5} \), but combined ACh and BAY K significantly shifted \( V_{0.5} \) to a hyperpolarized voltage (\( V_{0.5} \): basal, \(-4.1 \pm 0.8 \text{ mV} \); ACh, \(-3.5 \pm 0.9 \text{ mV} \); ACh + BAY K, \(-11.6 \pm 1.7 \text{ mV} \); \( P = 0.0006 \), ANOVA) (Fig. 5D). ACh did not have significant effects on the amplitude and the voltage dependence of activation of \( I_{\text{Ca,L}} \) in F HVMS (data not shown). These results support the idea that the phosphorylation state of the LTCC is increased in F HVMS, and this is responsible for the diminished effect of BAY K.

**BAY K effects on \( I_{\text{Ca,L}} \) in LVAD HVMS are normalized.** Previous studies have shown that LVAD support of the failing human heart induces reverse remodeling at the molecular, cellular, and organ levels (45). Particularly, LVAD support improves adrenergic contractile responsiveness (12). We tested whether the response of \( I_{\text{Ca,L}} \) to BAY K in LVAD HVMS was greater than in F HVMS. BAY K significantly increased \( I_{\text{Ca,L}} \) in LVAD HVMs with maximal \( I_{\text{Ca,L}} \) density increased by 128 \( \pm 39 \% \) (basal: \(-8.1 \pm 1.4 \text{ pA/pF} \); BAY K: \(-16.1 \pm 1.1 \text{ pA/pF} \), \( n = 6 \), \( N = 3 \)). These effects are comparable to those in NF HVMS (Fig. 6, A and C). BAY K tended to cause a leftward shift of the activation of \( I_{\text{Ca,L}} \) in LVAD HVMs (\( V_{0.5} \): basal, \(-6.76 \pm 3.17 \text{ mV} \); BAY K, \(-9.42 \pm 3.23 \text{ mV} \); \( P = 0.10 \), \( \Delta V_{0.5} \): \(-2.66 \pm 1.19 \text{ mV} \) (Fig. 6D), and \( V_{0.5} \) after BAY K was not different among NF, F, and LVAD HVMS (\( P = 0.73 \)). BAY K also significantly accelerated the decay of \( I_{\text{Ca,L}} \) (Fig. 6B). These results show that the effect of BAY K on \( I_{\text{Ca,L}} \) density is normalized by LVAD, but the effect on \( I_{\text{Ca,L}} \) voltage dependence of activation is not. This suggests that the mechanisms controlling the increase in \( I_{\text{Ca,L}} \) amplitude and shift in \( V_{0.5} \) upon phosphorylation of the LTCC could be distinct, possibly controlled by different protein phosphatases (28).

**Interactive effects of BAY K and adrenergic stimulation (Iso or DBcAMP) on \( I_{\text{Ca,L}} \) in LVAD HVMs.** We showed in a previous study that LVAD support normalizes the adrenergic responsiveness of the \( I_{\text{Ca,L}} \) (8). In the present study we tested the interactions between the effects of BAY K and Iso or DBcAMP on \( I_{\text{Ca,L}} \) in LVAD HVMs. Iso increased \( I_{\text{Ca,L}} \) by 50 \( \pm 9% \) in LVAD HVMS (basal vs. Iso: \(-10.7 \pm 1.3 \text{ vs. } -16.2 \pm 2.4 \text{ pA/pF} \), \( n = 5 \), \( N = 3 \); \( P < 0.05 \)). BAY K after Iso did not significantly increase \( I_{\text{Ca,L}} \) (\(-18.9 \pm 2.1 \text{ pA/pF} \); \( P = 0.25 \), unpaired \( t \)-test) (Fig. 7A). Iso shifted the voltage dependence of the activation of \( I_{\text{Ca,L}} \) to more negative voltages, and BAY K + Iso did not further shift this relationship (\( V_{0.5} \): basal, \(-9.3 \pm 1.8 \text{ mV} \); Iso, \(-14.4 \pm 1.6 \text{ mV} \); Iso + BAY K, \(-18.1 \pm 2.2 \text{ mV} \); \( P < 0.05 \), basal vs. Iso; \( P = 0.36 \), Iso vs. Iso + BAY K; one-way repeated ANOVA) (Fig. 7C). \( \tau_f \) was decreased by Iso as seen in NF HVMS, but no difference in \( \tau_f \) between basal and BAY K + Iso groups or between Iso and BAY K + Iso groups was found (Fig. 7D). \( \tau_f \) was not different among all three groups (data not shown).

DBcAMP increased \( I_{\text{Ca,L}} \) in LVAD HVMS (basal: \(-8.1 \pm 1.4 \text{ pA/pF} \); DBcAMP, \(-29.8 \pm 1.9 \text{ pA/pF} \); \( P < 0.01 \), unpaired \( t \)-test), and BAY K did not further increase \( I_{\text{Ca,L}} \) (DBcAMP, \(-31.1 \pm 2.9 \text{ pA/pF} \); \( P > 0.05 \)) (Fig. 7E and F). BAY K did shift \( I_{\text{Ca,L}} \) activation (\( V_{0.5} \): DBcAMP, \(-12.9 \pm 1.0 \text{ mV} \); DBcAMP + BAY K, \(-18.1 \pm 1.9 \text{ mV} \); \( P = 0.01 \), paired \( t \)-test) (Fig. 7F) but did not alter \( I_{\text{Ca,L}} \) decay in LVAD HVMS pretreated with DBcAMP (Fig. 7H).

**Effect of Iso on \( I_{\text{Ca,L}} \) in LVAD HVMS pretreated with BAY K.** For completeness, we tested whether BAY K reduced Iso effects on the LTCC. In LVAD HVMS pretreated with BAY K, Iso did not increase \( I_{\text{Ca,L}} \) (maximal \( I_{\text{Ca,L}} \): basal, \(-9.84 \pm 1.15 \text{ pA/pF} \); BAY K, \(-16.87 \pm 1.55 \text{ pA/pF} \); Iso + BAY K, \(-17.58 \pm 3.13 \text{ mV} \); \( P < 0.05 \), basal vs. BAY K; \( P > 0.05 \), BAY K vs. Iso + BAY K; one-way repeated ANOVA, \( n = 4 \), \( N = 2 \).
2), as in NF HVMs (Fig. 8, A and B). BAY K tended to enhance \(I_{\text{CaL}}\) decay \((P = 0.08)\), but BAY K + Iso did not slow \(I_{\text{CaL}}\) decay. Neither BAY K nor BAY K with Iso shifted the activation of \(I_{\text{CaL}}\) in LVAD HVMs, indicating a partial normalization of the properties of the LTCC (8).

**DISCUSSION**

The present study shows that BAY K 8644 has smaller effects on \(I_{\text{CaL}}\) in failing versus nonfailing HVMs. The reduction in BAY K effects on \(I_{\text{CaL}}\) in F HVMs was related to blunted effects of adrenergic agonists and alterations in \(I_{\text{CaL}}\) properties that are consistent with increased basal channel activity like those known to be induced by LTCC phosphorylation.

Are reduced BAY K effects on \(I_{\text{CaL}}\) responsible for diminished inotropic effect of BAY K in F HVMs? Several studies have shown a reduced inotropic effect of BAY K in failing myocardium (34, 39). BAY K increases contractility of cardiac myocytes mainly by enhancing \(I_{\text{CaL}}\), which induces Ca\(^{2+}\) release from the sarcoplasmic reticulum (18) and loads the sarcoplasmic reticulum (17). The reduced BAY K effects on \(I_{\text{CaL}}\) we observed can explain the reduced inotropic effect of BAY K in F HVMs shown in previous studies (1).

**Phosphorylation of the LTCC and adrenergic stimulation on \(I_{\text{CaL}}\)**. The LTCC is composed of four subunits, \(\alpha_1c\), \(\beta_\gamma\), and \(\alpha_2\delta\), of which \(\alpha_1c\) and \(\beta\) have consensus phosphorylation sites. In vitro it has been shown that the \(\alpha_1c\)-subunit is a good substrate for multiple protein kinases, including PKA, PKC, and Ca\(^{2+}\)/calmodulin-dependent kinase II (CaMK II) (28, 29). Conventionally, it is believed that adrenergic effects on myocyte LTCCs are mediated by the cAMP/PKA signaling pathway. Ser\(^{478}\) and Ser\(^{479}\) on the \(\beta_2a\)-subunit have also been shown to be phosphorylated by PKA (28, 29). The PKA phosphorylation sites on the \(\alpha_1c\)-subunit, which causes changes in channel biophysics (increased open probability) are still controversial and have been postulated to include Ser\(^{1928}\) (11, 20, 37) and Ser\(^{1901}\) (35) on the COOH terminus. Some studies suggest that chronic adrenergic stimulation, like that seen in congestive heart failure, activates CaMK II (24, 46, 50), which is capable of phosphorylating the LTCC and increasing the \(I_{\text{CaL}}\) (13). We cannot rule out the involvement of CaMK II-mediated phosphorylation when human myocytes are stimulated with Iso and DBcAMP, since the local Ca\(^{2+}\) concentration near the LTCC will be increased and could activate local CaMK II. Therefore, phosphorylation of the LTCC by both PKA and CaMK II can greatly increase the availability and the open probability of the LTCC, resulting in significant increase in macroscopic whole cell \(I_{\text{CaL}}\).

**Interaction between effects of BAY K and adrenergic agonists on the LTCC**. Adrenergic agonists increase LTCC availability and open probability by prolonging channel opening and inducing a highly active gating mode named mode 2 (48). It is generally believed that these effects are mediated by PKA-mediated phosphorylation (33, 48). Recently, there is also evidence indicating that adrenergic stimulation can activate CaMK II, which can also phosphorylate the LTCC and increase channel activity (13). The effects of BAY K on the LTCC are very similar to these effects (36, 48): increased availability, open probability, and mode 2 activity. These results suggest a commonality of BAY K and Iso effects. However, Tsien et al. (44) have suggested that Iso enhances \(I_{\text{CaL}}\) by augmenting LTCC availability and affecting fast kinetic processes like closing, whereas BAY K mainly promotes mode 2 activity of the LTCC.

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**Fig. 6.** Effects of BAY K on \(I_{\text{CaL}}\) in left ventricular assist device (LVAD)-supported HVMs (n = 6 cells, N = 3 hearts). A: representative recordings of maximal \(I_{\text{CaL}}\) before (basal) and after the application of BAY K in LVAD HVMs. B: BAY K decreased \(\tau_i\) at different test potentials in LVAD HVMs. C: I-V relationships in LVAD HVMs before and after BAY K. D: activation curves fitted with a Boltzmann equation in LVAD HVMs before and after the application of BAY K. BAY K caused a leftward shift of activation curves. \#P < 0.05; \&P < 0.01; \$P < 0.001 at the corresponding test potential. Bonferroni post hoc tests were done to compare the values at each test potential after 2-way repeated ANOVA test showed that the drug had significant effects on \(\tau_i\) and \(I_{\text{CaL}}\).
BAY K binds to S5 in domain III and to S6 in domains III (23) and IV (7) of the \( \alpha_{lc} \)-subunit, spatially distinct from the PKA and CaMK II phosphorylation sites [the COOH terminus of \( \alpha_{lc} \) and the \( \beta \)-subunit (28–30)]. The fact that adrenergic stimulation and BAY K do not exert their effects at the same locations on the LTCC does not exclude the possibility that they produce a common effect. Erxleben et al. (16) have suggested that BAY K may stabilize the phosphorylated LTCC.

Fig. 7. Effects of BAY K on \( I_{CaL} \) in LVAD HVMs pretreated with 1 \( \mu \)M Iso (\( n = 5 \) cells, \( N = 3 \) hearts) or 10 \( \mu \)M pipette DBcAMP (\( n = 5 \) cells, \( N = 2 \) hearts). A: representative recordings of maximal \( I_{CaL} \) under basal conditions, with Iso, and with combined BAY K and Iso in LVAD HVMs. B: \( I-V \) relationships under basal condition, with Iso, and with combined BAY K + Iso in LVAD HVMs. Iso increased \( I_{CaL} \) density, but further BAY K treatment did not increase \( I_{CaL} \). C: \( I_{CaL} \) activation curves under basal conditions, with Iso, and with combined BAY K and Iso. Iso shifted the activation of \( I_{CaL} \) to more negative voltages, but BAY K did not further shift the activation curve. D: \( \tau_r \) under basal conditions, with Iso, and with combined BAY K and Iso in LVAD HVMs. Iso significantly decreased \( \tau_r \), but BAY K + Iso did not slow down the decay of \( I_{CaL} \). In B and D: *\( P < 0.05 \), basal vs. Iso; #\( P < 0.05 \), basal vs. BAY K + Iso.

Fig. 8. Effects of 1 \( \mu \)M Iso on \( I_{CaL} \) in LVAD HVMs pretreated with BAY K (\( n = 4 \) cells, \( N = 1 \) hearts). A: representative recordings of maximal \( I_{CaL} \) under basal conditions, with BAY K, and with BAY K + Iso in LVAD HVMs. B: \( \tau_d \) under basal condition, with BAY K, and with combined BAY K and Iso in LVAD HVMs. BAY K significantly decreased \( \tau_d \), but BAY K + Iso did not further change \( I_{CaL} \) decay. C: \( I-V \) relationships under basal conditions, with BAY K, and with combined BAY K + Iso in LVAD HVMs. BAY K increased \( I_{CaL} \) density, but further Iso treatment did not increase \( I_{CaL} \). D: \( I_{CaL} \) activation in LVAD HVMs pretreated with DBcAMP and then DBcAMP + BAY K. *\( P < 0.05 \), control vs. BAY K; #\( P < 0.05 \), control vs. BAY K + Iso.
or mimic the effect of phosphorylation (16). We have measured the single-channel behavior after the application BAY K or Iso in normal feline ventricular myocytes and found that both drugs increase the availability, open probability, and mode 2 gating of the LTCC. When BAY K was included in the pipette, Iso did not have further stimulatory effects on the single-channel activities [data not shown but reported in an abstract (9)]. More detailed single-channel studies of Iso and BAY K effects on the LTCC in HVMs are needed to further define their mechanisms of actions.

Previous studies have also shown that combinations of BAY K with PKA-dependent phosphorylation produced marked slowing of $I_{CaL}$ and tail current decay (43). These results imply that BAY K might stabilize the phosphorylated state of the LTCC by retarding dephosphorylation (3) or that PKA-dependent phosphorylation might stabilize the BAY K-induced open state of the LTCC. The present study cannot resolve these issues.

**Does the LTCC have increased phosphorylation in F HVMs?** We (8) and others (41) have observed that the LTCC behaves as if it is “hyperphosphorylated” in F HVMs. To date, there is no direct biochemical evidence for enhanced phosphorylation of the LTCC in heart failure, due to the technically demanding nature of these studies: There are many unresolved issues regarding LTCC phosphorylation. The COOH terminus of the $\alpha_{1C}$-subunit, where the PKA phosphorylation site (Ser$^{1928}$) is thought to be located, has been reported to be cleaved (21) from the protein. Phosphorylation could be mediated by both PKA and CaMK II, which has been shown to be activated in failing myocardium(24). There are PKA sites on the $\beta$-subunit (22), and there are multiple $\beta$-isofoms ($\beta_1$, $\beta_2$, and $\beta_3$, each having splicing isoforms). However, there is strong indirect evidence for greater phosphorylation of the LTCC in heart failure. Schroder et al. (41) showed that there were increased open probability and availability of the LTCCs in F HVMs, which resembled the effects of 8-bromo-cAMP and a phosphatase inhibitor, okadaic acid. They concluded that there could be increased phosphorylation of the LTCC in the failing heart due to decreased phosphatase activities. Our previous study (8) of the LTCC in F HVMs is consistent with these findings.

The present results strongly support the idea that adrenergic agonists and BAY K increase $I_{CaL}$ through a common mechanism(s) that can be saturated (summarized in Fig. 9). Therefore, when the effects of one agent are large, there is little effect of the other agent. These results suggest that both LTCC phosphorylation induced by adrenergic agonists and BAY K can induce a maximal increase in $I_{CaL}$ availability, open probability, and/or mode 2 gating and the voltage dependence of activation. The effects of BAY K were smaller in F than in NF HVMs, consistent with the hypothesis that the basal phosphorylation state of the LTCC is increased in the failing human heart. BAY K had greater effects on cells pretreated with dephosphorylating agents such as ACh, which further support a higher phosphorylation state of the LTCC in failing myocytes. Several approaches were used to dephosphorylate the LTCC. These included dialysis of cells with the catalytic subunit of phosphatases, inorganic phosphatases such as 2,3-butanedione monoxime (BDM), and activation of endogenous phosphatases by ACh. Experiments with phosphatases in the pipette solution are technically demanding, since diffusion of phosphatases into myocytes is very slow. Two cells were studied with this approach, and increased BAY K effects on phosphatase-pretreated cells were observed (data not shown). The mechanism of action of BDM on $I_{CaL}$ is controversial, with some studies showing its effect is related to its inorganic phosphate activity (14, 19) and others suggesting a direct LTCC blocking effect (2). We tested BDM on NF and F HVMs and found that its effects on $I_{CaL}$ are very rapid, consistent with the blocker model (data not shown). Thus we used ACh as the primary approach to activate endogenous phosphatase activity, acknowledging the fact that ACh may also activate protein kinase G to inhibit $I_{CaL}$ in F HVMs (47). Arguing against this idea is the fact that ACh did not significantly change $I_{CaL}$ in NF HVMs. Collectively, our indirect approaches support the idea that increased basal LTCC phosphorylation is responsible for the reduced effects of Iso, BAY K, and DBCAMP on $Ca^{2+}$ current in failing human myocytes.

**Response of $I_{CaL}$ to Iso is normalized in LVAD HVMs.** LVAD support of the failing human heart at least partially normalizes cardiac function and adrenergic regulation (6). We have previously shown that abnormal adrenergic effects on contraction and $Ca^{2+}$ transients in failing myocytes are restored toward normal after LVAD (8, 12). In the present study we showed that the increase of $I_{CaL}$ amplitude by BAY K is also normalized after LVAD. These findings are consistent with the idea that the beneficial remodeling induced by LVAD is related to the normalization of sympathetic neurohormones (6) and/or the mechanical unloading of the heart. We specifically propose that hyperphosphorylation of PKA target proteins, such as the LTCC, is reduced after LVAD support. However, the normalization of the LTCC properties is not complete, since the voltage-dependence of activation of the LTCC remains shifted to more negative voltages.

**Limitations.** All studies using tissue from end-stage heart failure patients suffer from the fact that there is tremendous...
patient-to-patient variability in disease etiologies, treatments, and a host of other factors. In addition, the limited number of available hearts leads to a small sample size in some portions of the study. Finally, the nonfailing (control) group does not necessarily reflect normal human tissue.

Conclusion. The diminished effects of BAY K 8644 on ICa,L in F HVMs appears to result from a higher basal phosphorylation state of the LTCC due to high adrenergic activity and/or lower phosphatase activity. LVAD support of failing heart normalizes the response of ICa,L to BAY K 8644. These results support the idea that an increase in basal LTCC activity in failing human myocytes is responsible for the reduced inotropic effects of agonists of agents that induce their effects by increasing ICa,L.

REFERENCES


