Mechanisms of Altered Excitation-Contraction Coupling in Canine Tachycardia-Induced Heart Failure, I

Experimental Studies

Brian O’Rourke, David A. Kass, Gordon F. Tomaselli, Stefan Kääb, Richard Tunin, Eduardo Marbán

Abstract—Pacing-induced heart failure in the dog recapitulates many of the electrophysiological and hemodynamic abnormalities of the human disease; however, the mechanisms underlying altered Ca\(^{2+}\) handling have not been investigated in this model. We now show that left ventricular midmyocardial myocytes isolated from dogs subjected to 3 to 4 weeks of rapid pacing have prolonged action potentials and Ca\(^{2+}\) transients with reduced peaks, but durations \(\approx 3\)-fold longer than controls. To discriminate between action potential effects on Ca\(^{2+}\) kinetics and direct changes in Ca\(^{2+}\) regulatory processes, voltage-clamp steps were used to examine the time constant for cytosolic Ca\(^{2+}\) removal (\(\tau_{ca}\)). \(\tau_{ca}\) was prolonged by just 35% in myocytes from failing hearts after fixed voltage steps in physiological solutions (\(\tau_{ca}\) control, 216 ± 25 ms, \(n=17\); \(\tau_{ca}\) failing, 292 ± 23 ms, \(n=22\); \(P<0.05\)), but this difference was markedly accentuated when Na\(^+/\)Ca\(^{2+}\) exchange was eliminated (\(\tau_{ca}\) control, 282 ± 30 ms, \(n=13\); \(\tau_{ca}\) failing, 576 ± 83 ms, \(n=11\); \(P<0.005\)). Impaired sarcolemmal Ca\(^{2+}\) uptake and a greater dependence on Na\(^+/\)Ca\(^{2+}\) exchange for cytosolic Ca\(^{2+}\) removal was confirmed by inhibiting SR Ca\(^{2+}\) ATPase with cyclopiazonic acid, which slowed Ca\(^{2+}\) removal more in control than in failing myocytes. \(\beta\)-Adrenergic stimulation of SR Ca\(^{2+}\) uptake in cells from failing hearts sufficed only to accelerate \(\tau_{ca}\) to the range of unstimulated controls. Protein levels of SERCA2a, phospholamban, and Na\(^+\)/Ca\(^{2+}\) exchanger revealed a pattern of changes qualitatively similar to the functional measurements; SERCA2a and phospholamban were both reduced in failing hearts by 28%, and Na\(^+\)/Ca\(^{2+}\) exchanger protein was increased 104% relative to controls. Thus, SR Ca\(^{2+}\) uptake is markedly downregulated in failing hearts, but this defect is partially compensated by enhanced Na\(^+\)/Ca\(^{2+}\) exchange. The alterations are similar to those reported in human heart failure, which reinforces the utility of the pacing-induced dog model as a surrogate for the human disease. (Circ Res. 1999;84:562-570.)

Key Words: excitation-contraction coupling \(\bullet\) action potential \(\bullet\) sarcoplasmic reticulum \(\bullet\) Ca\(^{2+}\) uptake \(\bullet\) heart failure

Recent evidence indicates that the hemodynamic alterations accompanying heart failure are coincident with a common pattern of electrophysiological and excitation-contraction (E-C) coupling changes at the cellular level. Hallmarks of heart failure include prolongation of the cardiac action potential,1–4 down-regulation of the repolarizing potassium currents \(I_{k}\) and \(I_{kr}\),1,5,6 decreased responsiveness to \(\beta\)-adrenergic stimulation,7–13 and alterations of intracellular Ca\(^{2+}\) handling.14–17 Studies of intact cardiac muscles18–20 or isolated myocytes21,22 indicate that developed force is depressed, relaxation is prolonged, and frequency-dependent facilitation of contraction is blunted in heart failure. These findings may be explained by underlying defects in cellular Ca\(^{2+}\) homeostasis. The amplitude of the intracellular Ca\(^{2+}\) transient and its rate of decay have been shown to be reduced in intact muscles15 and in isolated ventricular myocytes23,24 from failing human hearts.

Although there is strong evidence that intracellular Ca\(^{2+}\) removal is suppressed in heart failure, there is still controversy about which Ca\(^{2+}\) regulatory proteins are responsible for the changes in Ca\(^{2+}\) homeostasis. Numerous investigators have reported that the levels of sarcolemmal Ca\(^{2+}\) ATPase (SERCA2A) mRNA are reduced by \(\approx 50\%\) in human heart failure (reviewed in References 25 and 26), and Hasenfuss et al18 reported a 30% to 40% reduction of SERCA2A protein levels by Western blot associated with a reduction in SR \(\text{Ca}^{2+}\) uptake. The latter result contrasts with several reports that have shown no change in pump protein level,27–29 either with or without a concomitant change in function. Similar disparate results have been reported for the Ca\(^{2+}\) ATPase regulatory protein phospholamban (PLB), ie, reduced message levels, but there is disagreement about whether PLB protein expression is decreased. Na\(^+\)/Ca\(^{2+}\) exchange, the other major Ca\(^{2+}\) removal system of the heart, is apparently upregulated in the failing heart. mRNA levels of the exchanger were shown to be increased 55% to 79%31–32 in human dilated cardiomyopathy, while the amount of Na\(^+\)/Ca\(^{2+}\) exchange in heart failure.

Received April 27, 1998; accepted December 18, 1998.
From the Section of Molecular and Cellular Cardiology, Division of Cardiology, Department of Medicine, The Johns Hopkins University, Baltimore, Md.

This manuscript was sent to Harry A. Fozzard, Consulting Editor, for review by expert referees, editorial decision, and final disposition.
Correspondence to Brian O’Rourke, PhD, Division of Cardiology, Department of Medicine, The Johns Hopkins University, 844 Ross Building, 720 Rutland Avenue, Baltimore, MD 21205. E-mail bor@jhmi.edu

© 1999 American Heart Association, Inc.

Circulation Research is available at http://www.circresaha.org
Ca\textsuperscript{2+} exchange protein was increased 36% to 160% in several studies.\textsuperscript{31-34} It has been suggested that the reduction in SR function, coupled with compensatory upregulation of Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange, may underlie the blunted force-frequency relation and postrepetent potentiation evident in heart failure, but it may also serve as a positive inotropic mechanism under Na\textsuperscript{+}-loaded conditions.\textsuperscript{32}

The present study examines in detail the E-C coupling alterations in the canine ventricular tachycardia-induced heart failure model to investigate the mechanism underlying the prolongation of Ca\textsuperscript{2+} removal. In addition, the profile of altered Ca\textsuperscript{2+} regulatory proteins was assessed by Western blot analysis. The finding that the burden of Ca\textsuperscript{2+} removal is shifted from SR Ca\textsuperscript{2+} uptake to Ca\textsuperscript{2+} extrusion via Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange is similar to what is thought to occur in human heart failure, supporting the notion that a fundamental program of ionic and E-C coupling alterations is induced by heart failure. The contribution of these changes to the shape and duration of the cardiac action potential and intracellular Ca\textsuperscript{2+} transient are tested by incorporating the experimental results into a computer model of the canine cardiomyocyte, as described in the accompanying study.\textsuperscript{35}

**Materials and Methods**

**Pacing-Induced Failure Protocol and Isolation of Midmyocardial Cardiomyocytes**

Induction of heart failure and ventricular cardiomyocyte isolation were carried out as described previously\textsuperscript{4} using protocols approved by the institution’s Animal Care and Use Committee. In brief, mongrel dogs of either sex were anesthetized and surgically instrumented under sterile conditions for implantation of a VVI pacemaker (Medtronic). Rapid pacing at 240 bpm was initiated 1 to 2 days after surgery and maintained for 3 to 4 weeks. At terminal heart failure (verified by hemodynamic measurements),\textsuperscript{a} hearts were harvested by left lateral thoracotomy, immersed in ice-cold saline, and quickly excised. Control hearts were similarly obtained from nonpaced dogs. The region of the ventricle perfused by the left anterior descending coronary artery was excised, cannulated, and perfused at 15 mL/min with nominally Ca\textsuperscript{2+}-free modified Tyrode’s solution (in mmol/L, NaCl 138, KCl 4, MgCl\textsubscript{2} 1, NaH\textsubscript{2}PO\textsubscript{4} 0.33, glucose 10, and HEPES 10 [pH 7.2 with NaOH]) or a physiological ionic composition consisting of (in mmol/L) sodium glutamate 130, CsCl 20, MgCl\textsubscript{2} 0.5, MgATP 5, and HEPES 10 (pH 7.2 with CsOH) and 80 μmol/L indo-1.

Borosilicate glass pipets of 1- to 4-MΩ tip resistance were used for whole-cell recording of action potentials or membrane currents with an Axopatch 200A amplifier coupled to a Digidata 1200A personal computer interface (Axon Instruments). A xenon arc lamp was used to excite indo-1 fluorescence at 365 nm (390 nm dichroic mirror), and the emitted fluorescence was recorded using a dual channel photomultiplier tube assembly (ESP associates, Toronto, Ontario) at wavelengths of 405 and 495 nm. Cellular autofluorescence at both emission wavelengths was recorded before capturing the cell-attached patch. Electrophysiological and fluorescence signals were acquired simultaneously and analyzed offline with custom-written software (IonView, B. O'Rourke).

On establishing the whole-cell configuration, 10-mV depolarizing test pulses from a holding potential of –80 mV were applied to examine the passive membrane properties of the myocytes. Cell capacitance (C\textsubscript{m}), determined by integrating the area under the capacitive current trace (control, 152±8 pF, n=9; failing, 175±8 pF, n=28), and series resistance (control, 7.8±1.0 MΩ, n=9; failing, 6.1±0.6 MΩ, n=28), determined from the exponential time constant of current decay (R\textsubscript{c},R\textsubscript{m}), did not differ between groups. Membrane capacitance and series resistance were electrically compensated by 70 to 75% for an estimated maximal voltage error of <3 mV in voltage-clamp mode. Compensation was disabled in current-clamp mode. Data have been corrected post hoc for the measured liquid junction potentials between the pipet and bath solutions as described.\textsuperscript{36}

The ratio of indo-1 fluorescence (F\textsubscript{ indo-1}/F\textsubscript{ indo-1 + Indo-1}\textsubscript{ 1000}) was determined after subtraction of cellular autofluorescence and was used to calculate free intracellular Ca\textsuperscript{2+} according to the equation [Ca\textsuperscript{2+}] = K\textsubscript{o}B(R\textsubscript{ indo-1} - R\textsubscript{ indo-1 + Indo-1}),\textsuperscript{37} where K\textsubscript{o} is 844 μmol/mL, as reported for rabbit cardiomyocytes.\textsuperscript{38} The average R\textsubscript{ indo-1/ indo-1 + Indo-1}, and β for the fluorescence system were determined by sequential exposure of cardiomyocytes to (1) a zero-Ca\textsuperscript{2+} modified Tyrode’s solution (other components as described above) containing metabolic inhibitors (10 μmol/L 2-deoxyglucose and 100 μmol/L 2,4-dinitrophenol), (2) the same solution with 1 μmol/L EGTA and 20 μmol/L ionomycin (for R\textsubscript{ indo-1}), and (3) and a high Ca\textsuperscript{2+} Tyrode’s solution (5 μmol/L Ca\textsuperscript{2+} instead of EGTA) for determining R\textsubscript{ indo-1/ indo-1 + Indo-1}, and β were 1.24±0.09, 10.44±1.85, and 2.7±0.4, respectively (n=10).

The duration of action potential–stimulated Ca\textsuperscript{2+} transients was determined by measuring the time from electrical stimulation to the half-decay of the transient from its peak (CaD\textsubscript{50}). The time constant for Ca\textsuperscript{2+} removal (τ\textsubscript{Ca},) was determined by fitting a single exponential to the Ca\textsuperscript{2+} transient during the late phase of repolarization of the action potential or, for voltage clamp pulses, ~20 ms after returning to the holding potential after a stimulus. Peak systolic Ca\textsuperscript{2+} was measured at steady state for a given stimulation frequency, which usually occurred after 10 to 15 pulses to a single test potential.

**Western Blot Analysis**

Chunks of left ventricle from the same hearts used for physiological study were freeze-clamped in liquid nitrogen at the time of sacrifice and stored at –80°C. Frozen tissue samples were pulverized with a mortar and pestle, and 10 mL/g of wet tissue weight of lysis buffer was added on ice, the lysate was homogenized (two 15-second bursts) and centrifuged, and the supernatant was aliquoted into tubes and frozen for subsequent analysis. The protein concentration was assayed (BCA kit, Pierce Biochemicals), and 100 μL of lysate was added to an equal volume of sample buffer containing 50 μmol/L Tris-HCl, 10% glycerol, 2% SDS, 0.05% bromphenol blue, and 0.3 μmol/L DTT and boiled for 5 minutes. Triplicate samples from 1 control heart and 1 failing heart were loaded on each 5% to 15% polyacrylamide gradient gel (Ready Gel, Bio-Rad) along with duplicate samples from a control heart selected as a reference for data normalization. After electrophoretic separation at 200 V for 30 to 45 minutes in Tris-glycine/SDS buffer...
proteins were transferred to nitrocellulose membranes (Semi-Dry transfer blot, Bio-Rad), and non-specific antibody binding was blocked for 1 hour in PBS with 0.1% Tween-20 and 5% nonfat milk. Membranes were washed for 15 minutes in Tween/PBS and then incubated with the primary antibody of interest for 1 hour. Monoclonal anti-SERCA2 (catalog No. MA3-919), anti-PLB (catalog No. MA3-922) and anti-Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger (NCX) (catalog No. MA3-926) antibodies were purchased from Affinity BioReagents (Golden, CO). After washout of the primary antibody, membranes were incubated for 1 hour with anti-immunoglobulin horseradish peroxidase secondary antibody and extensively washed again before chemiluminescent detection on Hyperfilm enhanced chemiluminescence (Amersham Life Science, Inc).

Films were digitally scanned into a computer, and band densities were corrected for protein loading (which was approximately equal for all samples on a gel) and normalized to the average density of the reference lanes for comparison of control and failing heart samples. Band density was linearly related to protein loading (data not shown).

Statistical Analysis
Comparisons between groups were made using unpaired Student \( t \) tests or, for data spanning a range of conditions (eg, frequency dependence of action potential duration [APD]), by 2-factor ANOVA, followed by the Tukey test. ANCOVA was used to examine the relation between the Ca\textsuperscript{2+} transient duration and APD. A 95% CI was used to determine statistical significance.

Results

Action Potential–Stimulated Ca\textsuperscript{2+} Transients
Action potentials recorded at 37°C with minimal intracellular Ca\textsuperscript{2+} buffering (80 \( \mu \)mol/L indo-1) were prolonged in myocytes from failing hearts (Figure 1B) relative to those from control hearts (Figure 1A; 6-second cycle length). The morphology of the accompanying Ca\textsuperscript{2+} transients (Figure 1A and 1B, bottom panels) also differed, with the majority of transients in cells from failing hearts displaying a biphasic time to peak consisting of a fast peak at 43\( \pm \)6 ms\( (n=9) \) after stimulus and a slowly rising phase, which depended on the duration of depolarization. In Figure 1B, 2 examples of representative action potentials and Ca\textsuperscript{2+} transients are superimposed to illustrate the differential extent of SR impairment among cells from failing hearts. The large early peak in the transient, which is suppressed by ryanodine or cyclopiazonic acid (CPA; compare with Figure 5), represents Ca\textsuperscript{2+} release from the SR (compare with Figure 3 of Winslow et al.\textsuperscript{35} In contrast, the typical control myocyte had a Ca\textsuperscript{2+} transient with a rapid time to peak (32\( \pm \)6 ms, \( n=10 \); NS with respect to the failing group) and the onset of Ca\textsuperscript{2+} decay preceding repolarization. Despite a substantial amount of overlap of the data ranges between groups (as evidenced by the scatter plots in...
the effect of frequency on the APD (compare Figure 1C with Figure 2B). The latter finding suggested that the duration of the Ca$^{2+}$ transient was strongly influenced by membrane potential in myocytes from failing hearts. This was supported by correlating CaD$_{50}$ with APDs at 90% repolarization (APD$_{90}$) (Figure 2D). CaD$_{50}$ in myocytes from failing hearts was more dependent on APD than in controls, particularly at the 6-second cycle length. ANCOVA yielded a coefficient of variation of 0.69 for the failing group compared with 0.18 in controls. By analyzing the late exponentially decaying phase of the Ca$^{2+}$ transient (as illustrated in Figure 2A), it was also possible to detect an inherent defect in the time constant for Ca$^{2+}$ removal (t$_{Ca}$) in cells from failing hearts (Figure 2C). However, from action potential–stimulated Ca$^{2+}$ transients, it is difficult to distinguish inherent changes in Ca$^{2+}$ regulatory subsystems from altered Ca$^{2+}$ kinetics secondary to electrophysiological (ie, action potential waveform) changes. Therefore, the various Ca$^{2+}$ removal subsystems were selectively examined with voltage-clamp techniques.

**Voltage-Clamp–Stimulated Ca$^{2+}$ Transients in Physiological Solutions**

Voltage-clamp experiments permitted the direct measurement of the Ca$^{2+}$ removal rate at a fixed voltage (–97 mV) after a 200-ms-long depolarizing step (to +3 mV). Figure 3A and 3B shows representative membrane currents and Ca$^{2+}$ waveforms for myocytes from control and failing hearts. The membrane current records during the depolarizing step in physiological salt solution reflect overlapping Na$^{+}$ current, L-type Ca$^{2+}$ current, transient outward K$^{+}$ current, and transient outward Ca$^{2+}$–activated Cl$^{-}$ current, among others; therefore, we did not directly measure the amplitude of the I$_{Ca}$ under these conditions (see Figure 4 for comparisons of I$_{Ca}$ between groups in Na$^{+}$-free, K$^{+}$-free solutions). No significant difference in resting Ca$^{2+}$ was evident under these conditions; however, peak systolic Ca$^{2+}$ was reduced 40% to 50% in cells from failing hearts (mean data are shown in Figure 7). The time constant for Ca$^{2+}$ removal (t$_{Ca}$) was 35% longer in the failing group under physiological conditions (control, 216±25 ms, n=17; failing, 292±23 ms, n=22; P<0.05; Figure 3E).

**Voltage-Clamp–Stimulated Ca$^{2+}$ Transients in Na$^{+}$-Free Solutions**

The prolongation of t$_{Ca}$ in the failing group was markedly accentuated when cells were studied in Na$^{+}$-free, K$^{+}$-free intracellular and extracellular solutions (Figure 3C through 3E, –Na data). Under these conditions, t$_{Ca}$ almost exclusively represents the SR Ca$^{2+}$ uptake rate; mitochondrial and sarcolemmal Ca$^{2+}$ removal processes likely contribute <2% to the total Ca$^{2+}$ decay rate.9 In control cells, t$_{Ca}$ was prolonged by ≈30% in Na$^{+}$-free solution (282±30 ms, n=13) compared with physiological solutions. In cells from failing hearts, t$_{Ca}$ was prolonged by 97% (576±83 ms, n=11) relative to that in physiological solutions and was twice as slow as in the control group (P<0.005). Since Na$^{+}$-free conditions effectively eliminate Na$^{+}$/Ca$^{2+}$ exchange, the results indicate that myocytes from failing hearts have a greater reliance on Na$^{+}$/Ca$^{2+}$ exchange for removing Ca$^{2+}$ from the cytoplasm during a transient. The t$_{Ca}$ in Na$^{+}$-free solution is
a direct measure of the primary defect in Ca\(^{2+}\) removal in heart failure—suppressed SR Ca\(^{2+}\) uptake.

The alterations in Ca\(^{2+}\) handling were not due to differences in the amplitude of the trigger for Ca\(^{2+}\) release nor to a change in the voltage dependence of the evoked Ca\(^{2+}\) transient. In Na\(^{-}\)-free, K\(^{-}\)-free solutions, there was no difference in the voltage dependence or density of \(I_{Ca}\) between groups (Figure 4A and 4B). Similarly, the midpoint of activation of the Ca\(^{2+}\) transient and the position of the maximum of the Ca\(^{2+}\) transient versus-voltage curve were not altered by heart failure (Figure 4C and 4D). At potentials more positive than the peak of this curve, the voltage dependence of the Ca\(^{2+}\) transient appeared elevated with respect to the failing group (NS).

**Effect of Ca\(^{2+}\) ATPase Inhibition**

A second test of the hypothesis that Na\(^{+}/Ca^{2+}\) exchange accounts for a greater fraction of Ca\(^{2+}\) removal in cells from failing hearts was to determine the rate of Ca\(^{2+}\) removal with SR uptake blocked. The SR Ca\(^{2+}\) ATPase inhibitor CPA (100 \(\mu\)mol/L) reduced the amplitude of the Ca\(^{2+}\) transient and greatly prolonged Ca\(^{2+}\) removal in both experimental groups (Figure 5A). This effect was larger in the control group, and the final \(t_{Ca}\) in CPA was 46% slower in the control group than in the failing group (Figure 5B). In the presence of CPA, \(t_{Ca}\) increased by 236\(\pm\)42% (\(n=9\)) in myocytes from control hearts as compared with an increase of only 102\(\pm\)31% (\(n=8\); \(P<0.05\)) in the failing group (Figure 5C). The results indicate that during a physiological Ca\(^{2+}\) transient, a greater fraction of Ca\(^{2+}\) removal is contributed by Na\(^{+}/Ca^{2+}\) exchange than by SR Ca\(^{2+}\) uptake in failing myocytes.

**Effect of \(\beta\)-Adrenergic Stimulation**

There is evidence that \(\beta\)-adrenergic receptors are decreased in heart failure\(^{7-13}\); thus it was of interest to determine the extent
to which the limitations of SR Ca\(^{2+}\) handling could be reversed by inotropic intervention. With Na\(^+\)/Ca\(^{2+}\) exchange blocked using Na-free solutions, the ability to upregulate SR Ca\(^{2+}\) uptake by \(\beta\)-adrenergic stimulation was assessed by treatment with isoproterenol (ISO; 1 \(\mu\)mol/L). ISO accelerated \(t_{Ca}\) in both experimental groups (Figure 6A); however, the absolute \(t_{Ca}\) remained significantly longer in the failing group under \(\beta\)-adrenergic stimulation and fell within the range of unstimulated controls (control \(t_{Ca}\), 66±4 ms, \(n=7\); failing \(t_{Ca}\), 207±65 ms, \(n=7\); \(P<0.05\)). The change in \(t_{Ca}\) (\(\Delta t_{Ca}\)) was significantly greater in myocytes from failing hearts (Figure 6C), perhaps owing to the slow initial rate, but the percentage decrease in \(t_{Ca}\) was similar in both groups (≈70%; Figure 6C).

**Effect of Frequency on Ca\(^{2+}\) Transients**

A significant shift toward transsarcolemmal Ca\(^{2+}\) extrusion coupled with downregulation of SR Ca\(^{2+}\) uptake would be expected to result in decreased loading of the SR at faster pacing frequencies. In this regard, suppressed frequency-dependent enhancement of contraction has been demonstrated in human heart failure.\(^{18,20,32,40}\) In physiological solutions under voltage-clamp conditions, control myocytes had higher peak systolic Ca\(^{2+}\) levels over a wide range of frequencies compared with cells from failing hearts, and the frequency-dependent enhancement of Ca\(^{2+}\) transient amplitude evident in controls at the 1-second cycle length was absent in the failing group (Figure 7).

### Ca\(^{2+}\) Regulatory Protein Expression in Heart Failure

Western blots were used to determine whether the physiological changes in Ca\(^{2+}\) handling with heart failure were correlated with altered protein levels of SERCA2, PLB, and NCX. As is clearly evident in the representative western blots shown in Figure 8A, the pattern of altered protein expression in failing hearts was in line with the idea that SERCA2 is downregulated in heart failure. Both SERCA2 and PLB were reduced by ≈28% in failing hearts (Figure 8B), with no change in the ratio of SERCA2 to PLB. NCX levels were increased by 104% in failing hearts relative to controls (Figure 8B).
Discussion

Mechanistic studies of human heart failure are complicated by the prolonged time course of development of the disease, the technical challenges of isolating cardiac tissue or cells from explanted hearts, the inability to investigate the early time course of cellular alterations, and the lack of control over experimental conditions. Thus, it is fortunate that the canine tachycardia-induced heart failure model so closely reproduces the known hemodynamic and ionic changes that have been identified in human hearts. The present findings indicate that, in addition to the electrophysiological changes noted in earlier studies, significant alterations in Ca\(^{2+}\) handling occur in isolated myocytes from failing hearts, following the general pattern of human studies. Through biochemical and functional measurements in the same hearts, we have found strong evidence in support of the hypothesis that the induction of heart failure triggers a shift in the balance of cytosolic Ca\(^{2+}\) extrusion mechanisms from SR Ca\(^{2+}\) uptake toward transsarcolemmal Ca\(^{2+}\) removal.

The decrease in peak systolic Ca\(^{2+}\) and prolongation of \(\tau_{Ca}\) are in good agreement with data obtained from human myocytes isolated from terminally failing hearts; however, we observed no statistically significant increase in resting Ca\(^{2+}\). The latter may be explained if Na\(^+\)/Ca\(^{2+}\) exchange fully compensates for the reduction of SR Ca\(^{2+}\) uptake in this experimental model. Recent evidence suggests that in human heart failure, the extent of diastolic dysfunction was inversely

![Figure 6. Effects of \(\beta\)-adrenergic stimulation of SR Ca\(^{2+}\) uptake.](image)

A. Acceleration of SR Ca\(^{2+}\) uptake with \(\beta\)-adrenergic stimulation (1 \(\mu\)mol/L ISO) in myocytes from control (left) and failing (right) hearts. Ca\(^{2+}\) transients were elicited by voltage-clamp steps in Na\(^+\)-free, K\(^+\)-free solutions at a 6-second cycle length. B. \(\tau_{Ca}\) values from individual myocytes before (pre-ISO) and after (ISO) \(\beta\)-adrenergic stimulation. Lines connect means and SE bars of the data sets. *\(P<0.05\) for comparison of \(\tau_{Ca}\) in control and failing groups in the presence of ISO. C. \(\beta\)-Adrenergic stimulation decreased \(\tau_{Ca}\) by \(\sim 70\%\) in both experimental groups (right), but the absolute change in \(\tau_{Ca}\) (\(\Delta\tau_{Ca}\); left) was significantly larger in the failing group (†\(P<0.01\)). Data were obtained under Na\(^+\)-free conditions for \(n=7\) myocytes from 3 hearts in each group.

![Figure 7. Frequency dependence of the Ca\(^{2+}\) transient.](image)

Peak systolic Ca\(^{2+}\) was higher in myocytes from control hearts over a range of cycle lengths compared with those in the failing group. Enhancement of the transient at the 1-second interval was absent in cells from failing hearts. Ca\(^{2+}\) transients were elicited by voltage-clamp steps in physiological solutions as in Figure 3A and 3B. *\(P<0.05\). Data are mean \(\pm\) SE.

![Figure 8. Levels of proteins involved in Ca\(^{2+}\) homeostasis in control and failing hearts.](image)

A. Western blots showing typical band densities of PLB, SERCA2a, and NCX in control and failing hearts (C indicates control, and F, failing). Arrows indicate positions of molecular weight markers run concomitantly. B. Levels of PLB, SERCA2a, and NCX normalized to a reference sample as described in Materials and Methods. Data are from 8 control hearts and 8 failing hearts. *\(P<0.05\); †\(P<0.01\).
correlated with upregulation of Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange protein.\textsuperscript{41} Our observations that the level of NCX protein was approximately double that of control hearts, and the lack of a rise in resting Ca\textsuperscript{2+}, indicate that Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange effectively compensates for defective SR Ca\textsuperscript{2+} removal from the cytoplasm. Although there was strong evidence that the fractional contribution of Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange to Ca\textsuperscript{2+} removal during a transient was increased in myocytes from failing cells, the relatively small increase in \( \tau_c \) (46%) in the presence of CPA indicates that the function of the NCX may not be increased as much as the protein levels would indicate. This is borne out by the results of the modeling studies, in which only a 53% to 75% functional enhancement of Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange was estimated by constraining the SR Ca\textsuperscript{2+} uptake rate to the value determined experimentally in Na-free conditions.\textsuperscript{35} The extent of functional enhancement of Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange activity in the failing heart will require further investigation, including direct measurements of Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange current; however, even without an increase in the absolute density of Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange, a substantially larger Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange current will be generated during an action potential-evoked Ca\textsuperscript{2+} transient in a failing myocyte, as a result of the reduction in SR Ca\textsuperscript{2+} uptake. Conversely, the 6 to 10% decrease in SERCA2 protein levels is likely to be an underestimation of the functional impairment of SR Ca\textsuperscript{2+} uptake, which was 2-fold slower in myocytes from failing hearts (see Figure 3E, -Na bars, and Reference 35).

Impaired SR loading from the combined effect of reduced SR Ca\textsuperscript{2+} ATPase activity and enhanced transsarcolemmal extrusion could underlie the observed reduction in peak Ca\textsuperscript{2+} and frequency-dependent facilitation of Ca\textsuperscript{2+} transient amplitude. In this regard, in a parallel study, we have examined the effects of reducing SR Ca\textsuperscript{2+} ATPase and increasing Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange by the amounts determined experimentally in a computer model of the normal and failing canine cardiac cell.\textsuperscript{35} The effects on the Ca\textsuperscript{2+} transient were well reproduced in the model simulations, indicating that these alterations alone are sufficient to account for the data. We have not directly addressed alternative explanations for the failure-induced alterations in Ca\textsuperscript{2+} handling, which include impaired responsiveness of SR Ca\textsuperscript{2+} release channels,\textsuperscript{42,43} reduced L-type Ca\textsuperscript{2+} channel-to-SR Ca\textsuperscript{2+} release channel coupling,\textsuperscript{44} or loss of frequency-dependent Ca\textsuperscript{2+} current facilitation,\textsuperscript{45} instead focusing primarily on Ca\textsuperscript{2+}-removal mechanisms. As in our previous study,\textsuperscript{1} we observed no significant difference in peak L-type Ca\textsuperscript{2+} current density in myocytes from failing hearts when compared with controls; however, in light of the alterations in Ca\textsuperscript{2+} handling, we would expect that during a given action potential, differences in sarcolemmal subspace Ca\textsuperscript{2+} in heart failure would significantly influence Ca\textsuperscript{2+}-dependent fast inactivation of L-type Ca\textsuperscript{2+} channels. The possible contribution of this effect to action potential prolongation is explored in Winslow et al.\textsuperscript{35}

The 28% reduction of SERCA2 protein level is close to that reported by Hasenfuss et al\textsuperscript{18} for failing human heart. Unlike in earlier studies, however, PLB levels were reduced by a similar amount, and the ratio of SERCA2 to PLB was not changed. Thus, the functional deficit of SR Ca\textsuperscript{2+} uptake could not be explained by a disproportionately higher amount of PLB but still could involve a difference in the basal phosphorylation state of this protein. Even when phosphorylation was substantially increased by \( \beta \)-adrenergic stimulation, the SR Ca\textsuperscript{2+} uptake rate in myocytes from failing hearts was brought only to the level of unstimulated controls, implying a fundamental limitation to the extent of inotropic reserve through the \( \beta \)-adrenergic pathway.

Enhanced Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange activity during the Ca\textsuperscript{2+} transient (whether relative or absolute) may prove to be a pivotal mechanistic change occurring in heart failure. The clear beneficial effect of this Ca\textsuperscript{2+} removal mechanism is that it largely compensates for defective SR Ca\textsuperscript{2+} uptake. It has also been suggested that enhanced reverse-mode (Ca\textsuperscript{2+} entry) activity of the exchanger may provide inotropic support in the failing muscle.\textsuperscript{32} On the other hand, forward-mode Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange in the face of slowed SR Ca\textsuperscript{2+} uptake depletes the releasable pool of Ca\textsuperscript{2+} with repetitive stimulation, which would effectively unload the SR and alter the frequency-dependent response.\textsuperscript{39} Furthermore, since the exchanger is electrically unidirectional, it is likely to participate both directly and indirectly (by influencing SR Ca\textsuperscript{2+} load) in reshaping the action potential in the failing heart. In this regard, the most striking finding of the experimental and modeling studies is that alterations in Ca\textsuperscript{2+} handling can have major effects on the action potential waveform. In model simulations of minimally Ca\textsuperscript{2+}-buffered cardiomyocytes, decreasing the density of K currents has less effect on the duration of the action potential than does suppression of SR Ca\textsuperscript{2+} uptake with enhanced Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange.\textsuperscript{35} The latter effect may predispose failing heart cells to instabilities of repolarization such as early or delayed afterdepolarizations\textsuperscript{46} or to triggered activity, especially in Ca\textsuperscript{2+}-overloaded myocytes.

In summary, canine pacing-induced heart failure leads to alterations of both the electrophysiological and the Ca\textsuperscript{2+} handling properties of cardiomyocytes that are remarkably similar to those described for the human disease. The increased dependence on Na\textsuperscript{+}/Ca\textsuperscript{2+} exchange coupled with a reduction of SR Ca\textsuperscript{2+} uptake not only substantially alters the kinetics and amplitude of the Ca\textsuperscript{2+} transient, but is likely to contribute to the altered action potential waveform of the failing heart cell. Continued investigation into the interplay between Ca\textsuperscript{2+} handling and membrane potential will be crucial to understanding the pathophysiology of heart failure.

Acknowledgment

This work was supported by the Specialized Center of Research on Sudden Cardiac Death (NIH P50 HL52307) and RO1HL61711.

References


23. Movsesian MA, Flesch M, Krause EG, Erdmann E. Unchanged protein levels of SERCA II and phospholamban but reduced Ca2+-uptake and Ca2+-ATPase activity of cardiac sarcoplasmic reticulum from dilated cardiomyopathy patients compared with patients with nonfailing hearts. *Circulation* 1995;92:3202–3208.


28. Movsesian MA, Flesch M, Krause EG, Erdmann E. Unchanged protein levels of SERCA II and phospholamban but reduced Ca2+-uptake and Ca2+-ATPase activity of cardiac sarcoplasmic reticulum from dilated cardiomyopathy patients compared with patients with nonfailing hearts. *Circulation* 1995;92:3202–3208.


Mechanisms of Altered Excitation-Contraction Coupling in Canine Tachycardia-Induced Heart Failure, I: Experimental Studies
Brian O'Rourke, David A. Kass, Gordon F. Tomaselli, Stefan Kääb, Richard Tunin and Eduardo Marbán

_Circ Res._ 1999;84:562-570
doi: 10.1161/01.RES.84.5.562

_Circulation Research_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1999 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/84/5/562

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in _Circulation Research_ can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to _Circulation Research_ is online at:
http://circres.ahajournals.org//subscriptions/