Ca^{2+}-Related Signaling and Protein Phosphorylation Abnormalities Play Central Roles in a New Experimental Model of Electrical Storm

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Background—Electrical storm (ES), characterized by recurrent ventricular tachycardia/fibrillation, typically occurs in implantable cardioverter-defibrillator patients and adversely affects prognosis. However, the underlying molecular basis is poorly understood. In the present study, we report a new experimental model featuring repetitive episodes of implantable cardioverter-defibrillator firing for recurrent ventricular fibrillation (VF), in which we assessed involvement of Ca^{2+}-related protein alterations in ES.

Methods and Results—We studied 37 rabbits with complete atrioventricular block for \( \approx 80 \) days, all with implantable cardioverter-defibrillator implantation. All rabbits showed long-QT and VF episodes. Fifty-three percent of rabbits developed ES (\( \geq 3 \) VF episodes per 24-hour period; \( 103 \pm 23 \) VF episodes per rabbit). Expression/phosphorylation of Ca^{2+}-handling proteins was assessed in left ventricular tissues from rabbits with the following: ES; VF episodes but not ES (non-ES); and controls. Left ventricular end-diastolic diameter increased comparably in ES and non-ES rabbits, but contractile dysfunction was significantly greater in ES than in non-ES rabbits. ES rabbits showed striking hyperphosphorylation of Ca^{2+}/calmodulin-dependent protein kinase II, prominent phospholamban dephosphorylation, and increased protein phosphatase 1 and 2A expression versus control and non-ES rabbits. Ryanodine receptors were similarly hyperphosphorylated at Ser2815 in ES and non-ES rabbits, but ryanodine receptor Ser2809 and L-type Ca^{2+} channel \( \alpha \)-subunit hyperphosphorylation were significantly greater in ES versus non-ES rabbits. To examine direct effects of repeated VF/defibrillation, VF was induced 10 times in control rabbits. Repeated VF tissues showed autophosphorylated Ca^{2+}/calmodulin-dependent protein kinase II upregulation and phospholamban dephosphorylation like those of ES rabbit hearts. Continuous infusion of a calmodulin antagonist (W-7) to ES rabbits reduced Ca^{2+}/calmodulin-dependent protein kinase II hyperphosphorylation, suppressed ventricular tachycardia/fibrillation, and rescued left ventricular dysfunction.

Conclusions—ES causes Ca^{2+}/calmodulin-dependent protein kinase II activation and phospholamban dephosphorylation, which can explain the vicious cycle of arrhythmia promotion and mechanical dysfunction that characterizes ES. (Circulation. 2011;123:2192-2203.)

Key Words: calcium ■ electrical storm ■ heart failure ■ implantable cardioverter-defibrillator ■ signal transduction

Electrical storm (ES), characterized by repetitive episodes (generally defined as \( \approx 3 \) within 24 hours) of ventricular fibrillation (VF) and/or ventricular tachycardia (VT), is an increasing problem among implantable cardioverter-defibrillator (ICD) patients. Recent analyses of large clinical trials indicate a high risk of early mortality in patients who experience ES. Most of this excess risk is attributable to cardiac, nonsudden mechanisms, particularly progressive heart failure (HF). The molecular mechanisms underlying ES and associated mortality are poorly understood.

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Ca^{2+}-handling protein phosphorylation is a major control mechanism for cardiac contractility and relaxation. Increased activity of protein phosphorylation mediators like cAMP-
dependent protein kinase A (PKA), Ca\(^{2+}\)/calmodulin-dependent protein kinase II (CaMKII), and protein kinase C (PKC) and resulting hyperphosphorylation of Ca\(^{2+}\)-handling proteins are linked to mechanical dysfunction and arrhythmias.\(^4\)–\(^9\) CaMKII/PKA-mediated phosphorylation of ryanodine receptors (RyR2s) causes diastolic Ca\(^{2+}\) leak from the sarcoplasmic reticulum (SR), causing depletion of SR Ca\(^{2+}\) stores and arrhythmias related to delayed afterdepolarizations.\(^4\)–\(^7\) Hyperphosphorylation of L-type Ca\(^{2+}\) channels (LTCCs) by CaMKII modulates Ca\(^{2+}\) current, predisposing to early afterdepolarizations.\(^8\) PKC activation results in hypophosphorylation of phospholamban, enhancing phospholamban inhibition of SR Ca\(^{2+}\)-ATPase (SERCA2a) and impairing Ca\(^{2+}\) uptake into the SR.\(^9\),\(^10\) These findings, together with the fact that VF is associated with increased [Ca\(^{2+}\)],\(^11\),\(^12\) and that ES is associated with elevated sympathetic tone,\(^1\) led us to hypothesize that Ca\(^{2+}\)-handling alterations caused by changed expression and/or activation of Ca\(^{2+}\) signaling molecules may be responsible for ES-related negative outcomes. In the present study, we report a new experimental model that features repetitive episodes of ICD firing for recurrent VF, in which we tested this hypothesis.

**Methods**

All animal handling protocols were approved by the Animal Experimentation Ethics Committee of Nagoya University.

**Surgical Technique and Experimental Protocol**

Female New Zealand White rabbits (weight, 2.5 to 3.5 kg) were used. We created complete atrioventricular block and implanted ICDs (Medtronic) using methods described previously,\(^13\),\(^14\) with modifications. In brief, 2 unipolar pacing leads (6491, Medtronic) fixed to the right ventricular free wall were connected to an ICD through a Y adaptor (5866–38M, Medtronic) implanted subcutaneously in the back. A custom-made patch electrode was sutured subcutaneously in the chest wall (Figure 1A). Ventricular pacing at 150 bpm (maximum pacing rate available in the device) was instituted immediately after creating atrioventricular block to allow recovery from surgery. Seven days after surgery, the pacing rate was decreased to 90 bpm, and ICD settings were established under ketamine (25 mg/kg)/xylazine (5 mg/kg) anesthesia (day 0). To determine the defibrillation threshold, VF was induced twice by applying 50-Hz burst stimulation via the ICD. The ICD was then programmed to detect and treat VF (see below). Rabbits with complete atrioventricular block (CAVB) equipped with ICDs were subjected to sustained bradycardia with VVI pacing (90 bpm for \(~1\) week, followed by 60 bpm). CAVB rabbits that survived for \(~3\) months were euthanized (pentobarbital, 40 mg/kg IV). Left ventricular (LV) free-wall tissue samples were fast-frozen in liquid N\(_2\) and
stored at −80°C. Echocardiograms were obtained at day 0 and end of study.

**Implantable Cardioverter-Defibrillator Settings**
The VF detection interval was set <240 ms (>250 bpm), and the VT detection algorithm was disabled. The number of intervals to detect VF (NID) and to re-detect VF (NID-redetect) were programmed to maximum values available (120 of 160 and 30 of 40, respectively) to avoid inappropriate shocks for torsades de pointes (TdP)-like VTs, which occur frequently in CAVB-rabbits. Up to 6 defibrillation shocks were programmed to treat a detected VF episode. The first therapy was set to at least twice the defibrillation threshold. Figure 1B shows an example of therapy parameters. Mean defibrillation thresholds were not statistically different between groups (Figure 1C).

**Implantable Cardioverter-Defibrillator Interrogation and Real-Time Electrogram Recordings**
Approximately every 10 days, the ICD was interrogated under conscious conditions to assess the number of VF and VT episodes and obtain intracardiac electrogams of VF episodes and percentages of rhythm paced/sensed. Tachyarrhythmias that were ≥5 consecutive beats at >250 bpm (VF detection interval) and terminated spontaneously less than NID, were detected as non-sustained VT-episodes (Figure I in the online-only Data Supplement). ES was defined as ≥3 VF episodes per 24 hours. Real-time electrograms and electrogams between the active CAN and the patch electrode (CAN-patch electrogram) were recorded through the ICD programmer. Electrogram parameter measurements, including cycle length of escape rhythm and QT interval, were based on averages of 3 consecutive beats in the lead providing the clearest QT-interval definition. QT interval was corrected (QTc) according to the method of Carlson et al for rabbits with the following formula: QTc=QT−0.175×(RR−300).

**W-7 Administration**
The calmodulin antagonist W-7 (BIOMOL) was infused continuously in ES rabbits via an osmotic pump (2ML1, Alzet) that delivers the calmodulin antagonist W-7 were implanted subcutaneously into the abdomen for 7-day solutions continuously at 10 μL/h for 7 days. The pump was filled with 2 mL dimethyl sulfoxide/water (50:50 vol/vol) with or without W-7 50 mg. Under ketamine/xylazine anesthesia, 2 pumps without W-7 were implanted subcutaneously into the abdomen for 7-day baseline infusion. W-7 was then administered by 1 pump (W-7 50 mg) for 1 week, followed by 2 pumps (W-7 100 mg) for the subsequent week. During infusion, ICD interrogation was performed daily. The dosages were established on the basis of the study by Mazur et al, and caspase-3 (Santa Cruz). Band densities were quantified by densitometry, standardized to GAPDH (Fitzgerald), and normalized to the control sample. I-1 protein was enriched by an optimized trichloroacetic acid extraction procedure as described previously. Phosphorylation analysis for Ca,1.2 was obtained with Pro-Q Diamond stain technology. In brief, proteins electroblotted on polyvinylidene fluoride membranes were fixed and stained with the Pro-Q Diamond Phosphoprotein Blot Stain Kit (P33356, Invitrogen). The membrane was imaged with UV transillumination and ATTO Light Capture molecular imaging. Scans were quantified with CS Analyzer (ATTO, Tokyo, Japan).

**Real-Time Polymerase Chain Reaction**
Total RNA was extracted from 0.5- to 1.0-g LV samples with Trizol reagent (Invitrogen) according to the manufacturer’s protocols. To assess mRNA transcript levels by real-time reverse transcriptase polymerase chain reaction, the first-strand cDNA was first synthesized with the High Capacity Reverse Transcriptase Kit (Applied Biosystems). TaqMan primers and probes for hypertrophy marker genes, including rabbit atrial natriuretic factor, brain natriuretic peptide (designed with Custom TaqMan Gene Expression Assay Design Tool), β-myosin heavy chain, and control 18S, were purchased from Applied Biosystems. Real-time polymerase chain reaction was performed with an ABI prism 7700 sequence detector. The fluorescent amplification curve of the product was determined, and the cycle at which the fluorescence reached a threshold was recorded (Ct) in triplicate and averaged. To control for variability in RNA quantity, the measured abundances of hypertrophic marker genes were normalized to that of 18S with the formula ΔCt=Ct(detected genes)−Ct(18S). The relative expression in ES and ES+W-7 group control hearts) was then determined with the following relationship: gene expression=2−ΔΔCt, where ∆ΔCt=ΔCt(ES or ES+W-7)−ΔCt (control).

**Statistical Analysis**
All data are expressed as mean±SEM. Western blot band intensities are expressed normalized to GAPDH signal intensity for the same sample. Two-way repeated-measures ANOVA was performed for electrogram parameters with the use of mixed model methodology with group and time as main effects. In case of a significant interaction, Tukey tests were used to compare individual means. One-way ANOVA followed by Bonferroni-corrected t-test was used to evaluate differences in echocardiographic parameters and protein and mRNA expression among groups. Unpaired t-tests were used for single comparisons between non-ES and ES group measurements, and paired t-tests were used for comparison of echocardiographic parameters before and after W-7. Two-tailed P<0.05 indicated statistical significance. The authors had full access to and take responsibility for the integrity of the data. All authors have read and agree to the manuscript as written.

**Results**

**Model Characteristics**
Thirty-two CAVB rabbits with ICDs were followed for 76±5 days. All had Qtc prolongation and ICD-detected self-terminating VT before the first VF episode; 53% (17/32) subsequently developed ES. Figure 1D shows 3 VF episodes within <2 hours in an ES rabbit. This ES rabbit had 127 VF episodes and 6617 self-terminating VT episodes until euthanasia at day 90. ES appeared at day 20, occurred intermittently for 17 days, and then occurred continuously from day 78. Representative real-time electrograms during ICD interrogation in an ES and non-ES rabbit are shown in Figure 2A. The ES rabbit had a slow escape rhythm and QT prolongation/abnormal QTU complexes at day 71 compared with the non-ES rabbit at day 72. Figure 2B shows the daily number of VF episodes from the same rabbits. The ES rabbit had a progressive increase in VF episodes from day 67 until death.
at day 83. The stored electrogram of the last VF episode showed unsuccessful defibrillation with the sixth therapy after 5 programmed therapies for repeated postshock VF. In contrast, the non-ES rabbit had sporadic single VF episodes. Figure 2C summarizes time-dependent electrogram changes in all rabbits. The RR intervals of escape rhythms were longer in ES rabbits versus non-ES rabbits. In ES rabbits, QTc increased from 183±5 ms on day 10 to near steady state values (229±7 ms) by day 20. Although non-ES rabbits also showed increased QTc (from 187±3 ms to 215±6 ms by day 40), QTc was significantly greater in ES rabbits. The number of VF episodes per rabbit averaged 103±23 for ES rabbits and 3.2±0.9 for non-ES rabbits (P<0.001; Figure 2D) during follow-up periods of 78±8 and 70±8 days, respectively (P=0.53; Figure 1C). The number of self-terminating VT episodes was also substantially greater for ES rabbits (Figure 2D). ES development appeared rate dependent: Clustered VF episodes could be suppressed by increasing the pacing rate and reappeared on returning the rate to 60 bpm (Figure II in the online-only Data Supplement).

ES sometimes occurred early, and only transiently (Figure III in the online-only Data Supplement). Of 17 ES rabbits, 9 died prematurely. Six died during ES, with the last VF episode recording showing VF undersensing or defibrillation failure. Two were euthanized for severe pocket infection, and 1 died of unknown causes. The remaining 8 ES rabbits that survived for 89±7 days were used for immunoblotting studies. ES episodes in 5 rabbits and single VF episodes in 3 rabbits were documented within the 24 hours before euthanasia.

Of 15 non-ES rabbits, 7 surviving for 94±5 days were used for immunoblotting studies. All 7 rabbits had at least 50 self-terminating VT episodes within 24 hours of euthanasia. The remaining 8 died prematurely. Five died suddenly of VF with defibrillation failure, and 3 died of unknown causes.

**Echocardiography**

Figure 3A shows representative M-mode echocardiograms at day 0 (baseline) and at the end of follow-up. LV end-diastolic diameter increased similarly by >20%, in non-ES and ES rabbits (Figure 3B). LV fractional shortening decreased from 38±1% at day 0 to 32±1% in non-ES rabbits and more severely to 25±1% in ES rabbits (P=0.006 versus non-ES) by end of study (Figure 3C). There were no significant differences in interventricular septum or posterior LV wall thicknesses among groups (Figure 3D). Pleural effusions were observed in 4 of 7 ES rabbits but not in non-ES rabbits.

**Protein Kinases and Phosphatases**

Figure 4A shows representative immunoblots for CaMKII-P, CaMKIIθ, and calmodulin on 1 gel each. CaMKII-P expression was significantly increased by ∼500% and ∼165% in ES and non-ES rabbits, respectively, without significant change in total CaMKII expression. Fractional CaMKII autophosphorylation was ∼2 times greater in ES than in non-ES rabbits, suggesting striking CaMKII activation. Calmodulin expression was unaltered. CaMKII activation was also observed in the right ventricle (Figure IV in the online-only Data Supplement) and was qualitatively similar to LV changes. Immunoblots for PKαα catalytic subunit, PKCα-P, and total PKCα are shown in Figure 4B and for phosphatase proteins in Figure 4C. PKαα catalytic subunit expression was reduced similarly by 61% and 55% in ES and non-ES rabbits, respectively, whereas total PKCα and PKCα-P were unchanged (Figure 4D). Expression of PP1 and PP2A catalytic subunits was increased by ∼85% in ES rabbits only (Figure 4E).

**Phosphorylation of Ca_{i,1,2}, RyR2, and Phospholamban**

Figure 5 shows immunoblots for total and phosphorylated forms of key Ca^{2+}-handling proteins. The LTCC α-subunit Ca_{i,1,2} band was observed at the expected molecular mass of
Phosphoprotein bands corresponding to Cav1.2 were stronger in both non-ES and ES rabbits versus controls (Figure 5B), with a larger fractional Cav1.2 phosphorylation (≈500%) in ES versus non-ES rabbits (≈130%).

RyR2 has multiple phosphorylation sites including RyR2-Ser2815, phosphorylated by CaMKII,17 and RyR2-Ser2809, which can be phosphorylated by CaMKII and/or PKA.5,18

Figure 5A (bottom) shows representative immunoblots of total RyR2, CaMKII-phosphorylated RyR2-P2815, and PKA/CaMKII-phosphorylated RyR2-P2809. Fractional RyR2-P2815 phosphorylation was increased significantly in both ES and non-ES rabbits, but that of RyR2-P2809 was significantly increased, by ≈70%, in ES rabbits only (Figure 5C). Total RyR2 and calsequestrin expression were unaltered in either group.

Phospholamban is an endogenous inhibitor of SERCA2a function. Phospholamban phosphorylation causes phospholamban dissociation from SERCA2a and removes inhibition. SERCA2a activity and SR Ca²⁺ uptake are enhanced on phospholamban phosphorylation. Phospholamban is phosphorylated at Ser16 by PKA and at Thr17 by CaMKII.19

Figure 5D shows representative immunoblots for SERCA2a, phospholamban-P16, phospholamban-P17, and total phospholamban. Fractional phospholamban phosphorylation was greatly reduced in ES rabbits, by 96% at Ser16 and 89% at Thr17 (Figure 5E), whereas there was no statistically significant change in phospholamban phosphorylation in non-ES rabbits. SERCA2a and total phospholamban expression were unchanged (Figure 5E).

Data for expression/phosphorylation of myofibrillar proteins are shown in Figure V in the online-only Data Supplement. PKA-phosphorylated myosin-binding protein C and troponin-I were reduced by ≈75% and ≈50% in ES and by ≈66% and ≈47% in non-ES groups, respectively, which was compatible with similar reductions in PKAα catalytic subunit expression in both groups.

Protein Phosphatase I-1 Phosphorylation
PKP1 activity is modulated by protein phosphatase I-1, which is phosphorylated at Thr35 by PKA.9,10 PKA-phosphorylated I-1 inhibits PKP1, augmenting the phospholamban phosphorylation resulting from direct PKA action. PKCα phosphorylates I-1 at a different site, Ser67, suppressing I-1 inhibition of PKP1 and thereby reducing phospholamban phosphorylation.9,10 Figure VI in the online-only Data Supplement shows representative blots for total I-1, PKA-phosphorylated I-1 (I-1-P35), and PKCα-phosphorylated I-1 (I-1-P67). Bands were observed at the expected molecular mass.20 There were no significant differences among groups, suggesting that phospholamban dephosphorylation in ES rabbits is due to enhancement of protein phosphatase activity unrelated to changes in PKA or PKCα phosphorylation of I-1.

Direct Effects of VF/Defibrillation on CaMKII and Phospholamban Phosphorylation
CaMKII hyperphosphorylation is arrhythmogenic, and phospholamban dephosphorylation negatively affects SR Ca²⁺ stores and contractility. We considered the possibility that repeated VF and defibrillation can cause these changes, initiating a vicious cycle of self-reinforcing contractile failure and arrhythmogenesis. To examine the effect of repeated VF/defibrillation on protein phosphorylation, we obtained LV tissue samples from day 0 rabbits subjected to repeated VF
tissue was removed, fast-frozen in liquid N₂, and stored at −80°C. Figure 6A and 6B show representative immunoblots for CaMKII and phospholamban phosphorylation and corresponding mean data. CaMKII-P expression and fractional CaMKII phosphorylation were increased by ~400% and ~700%, respectively. Phospholamban phosphorylation was reduced at Ser16 and Thr17 by ~80% and ~50%, respectively, which was qualitatively similar to results in ES rabbit hearts.

We then tested whether repeated electrical shocks per se contribute to altered protein phosphorylation, using LV tissue samples from additional control rabbits that received ten 5-J shock pulses without VF induction over 1 hour. Unlike repeated VF/defibrillation cycles, electrical shocks alone did not reproduce the ES-associated Ca²⁺-handling protein changes (compare Figure 6C and 6D with Figures 4A, 5D, 6A, and 6B). These findings suggest thatVF/defibrillation and electrical shocks differentially modulate Ca²⁺ handling and that alterations associated with ES derive from repeated VF/defibrillation cycles rather than electrical shocks alone.

**Responses of ES Rabbits to Calmodulin Inhibition**

CaMKII activation results from Ca²⁺/calmodulin binding. Anderson and colleagues[^21] have demonstrated in rabbit models of drug-induced long-QT syndrome that the CaMKII inhibitor KN-93 suppresses early afterdepolarizations and that the calmodulin antagonist W-7 prevents torsades de pointes, suggesting that CaMKII is a proarrhythmic signal. In the present study, to assess the potential central role of Ca²⁺/calmodulin/CaMKII signaling in ES, we administered W-7 to ES rabbits. Figure 7A illustrates the response in 1 ES rabbit. Multiple VF and VT episodes were documented almost every day during baseline infusion of dimethyl sulfoxide. Both VF and VT episodes decreased transiently after initiating 50-mg W-7 infusion and disappeared completely with 100-mg W-7 infusion. After discontinuation of W-7, arrhythmias eventually recurred. One-week infusion of W-7 to 5 rabbits caused dose-dependent reductions in VF episodes (from 25±7 during dimethyl sulfoxide infusion to 13±4 with the lower dose and 2.0±0.9 with the higher dose), self-terminating VT episodes (from 2022±579 to 711±178 and 160±25, respectively), and ES days (from 3.8±0.7 to 1.5±0.6 and 0.3±0.2, respectively) over 1-week observation periods (Figure 7B). W-7 did not significantly alter RR interval or QTc (Figure VII in the online-only Data Supplement).

Five ES rabbits were added to study whether W-7 rescues LV dysfunction. We obtained LV tissue samples from ES rabbits at the end of W-7 infusion for molecular studies. Figure 7C shows representative M-mode echocardiograms in 1 ES rabbit before and after 2-week W-7 infusion. Mean echocardiographic parameters in 5 ES rabbits are summarized in Figure 7D. LV end-diastolic and end-systolic diameters were decreased significantly, by 11% and 19%, respectively, and LV fractional shortening was increased to 30±2% from 23±2% before infusion (P<0.047). Representative immunoblots show that CaMKII-P bands were attenuated by W-7 in ES rabbits (Figure 8A). Overall, W-7 significantly reduced CaMKII-P expression and fractional CaMKII phosphorylation (Figure 8B). Because CaMKII promotes apoptosis and

**Figure 4. A, Top, Representative immunoblots of autophosphorylated Ca²⁺/calmodulin-dependent protein kinase II (CaMKII-P), CaMKIIδ, calmodulin (CaM), and GAPDH in left ventricular tissue samples from 4 control (CTL), 4 non–electrical storm (ES), and 4 ES rabbits. B and C, Immunoblots of protein kinase A (PKA)α catalytic subunit, autophosphorylated protein kinase Cα (PKCα-P), total PKCα, protein phosphatases 1 and 2A (PP1 and PP2A). D and E, Mean±SEM band intensities corresponding to B and C in control (n=6 to 8), non-ES (n=5 to 7), and ES (n=6 to 8) groups. *P<0.05, **P<0.01 vs control; †††P<0.01 vs non-ES group.**
stimulates hypertrophic transcriptional programs, we examined whether the cardiomyopathic effects of CaMKII were inhibited by W-7. Compared with controls, ES rabbits showed significant increases in caspase-3 subunits (Figure 8C and 8D) and atrial natriuretic factor and brain natriuretic peptide mRNA expression (Figure 8E), which were not suppressed by W-7 treatment. These findings indicate that the beneficial effects of W-7 are not associated with suppression of biomarkers of apoptosis or cardiac hypertrophy.

Discussion

ES is a significant clinical problem with a substantial mortality rate, particularly in the ICD population. In this article, we report findings in an animal model of ES based on an arrhythmic substrate induced by severe bradycardia due to CAVB. ES, manifested as frequently recurrent VT/VF episodes, was observed in approximately half of CAVB rabbits equipped with ICDs and allowed us to assess associated changes in CaMKII and phospholamban, suggesting that they may result from ES rather than simply being an associated finding. Calmodulin inhibition with W-7 suppressed VT/VF episodes and rescued LV dysfunction in association with a significant reduction in CaMKII hyperphosphorylation.

Figure 5. A, Immunoblots for Ca,1,2-P and Ca,1,2 (top) and ryanodine receptor (RyR2), RyR2-P2815, RyR2-P2809, and calsequestrin (CSQ) (bottom). B and C, Mean±SEM protein expression and phosphorylation fraction in control (CTL) (n=8), non–electrical storm (ES) (n=7), and ES (n=8) rabbits. D, Immunoblots for sarcoplasmic reticulum Ca$^{2+}$-ATPase (SERCA2a), phospholamban (PLB), phospholamban-P16 (PLB-P16), and phospholamban-P17 (PLB-P17). E, Corresponding mean±SEM protein expression and phosphorylation fraction in control (n=8), non-ES (n=7), and ES (n=8) rabbits. *P<0.05, **P<0.01 vs control; †P<0.01 vs non-ES group.

Relationship to Previous Studies in Related Arrhythmogenic Animal Models

The cellular and molecular bases of arrhythmogenic ventricular remodeling in CAVB rabbits have been characterized previously. CAVB rabbit cardiomyocytes show action potential duration (APD) prolongation and increases in cell shortening, systolic Ca$^{2+}$ content, and SR Ca$^{2+}$ load is increased by APD prolongation and enhanced SR Ca$^{2+}$ uptake due to phospholamban hyperphosphorylation, leading to increased systolic Ca$^{2+}$ release.

The findings in the present study of ES rabbits show some similarities and differences relative to previous work in...
shorter-term CAVB rabbits. QT prolongation and CaMKII
hyperphosphorylation are prominent in both. However, phos-
pholamban was dephosphorylated in ES rabbits, in contrast to
phospholamban hyperphosphorylation in rabbits with 2-week
CAVB. Perhaps as a result, contractility was reduced in ES
rabbits, contrasting with hypercontractility in shorter-term
CAVB. The discrepancies may be partly due to the effects of
repeated VF/defibrillation, which directly induces phospho-
lamban dephosphorylation (Figure 6B).

The striking CaMKII hyperphosphorylation (indicating
CaMKII autophosphorylation and activation) and phospho-
lamban dephosphorylation observed in the present study are
likely key findings. CaMKII-P expression was increased
5.7-fold in ES rabbits, a level exceeding changes seen
previously in other arrhythmogenic animal models, including
CaMKIIδ-overexpressing mice (≈3-fold wild-type values),7
CaMKIV-overexpressing mice (CaMKII-P data not shown,
but CaMKII activity increased ≈1.5-fold),8 rabbits with HF
after aortic banding/regurgitation (≈1.5-fold),24 and 2-week
CAVB rabbits (≈2.5-fold),23 whereas changes in non-ES
rabbits remained comparable to previous reports. CaMKII
activation causes RyR2 hyperphosphorylation, producing
RyR diastolic Ca^{2+} leak that promotes both HF (because of
loss of SR Ca^{2+}) and arrhythmogenesis (via arrhythmogenic
afterdepolarizations).22,25,26 CaMKII activation also increases
LTCC phosphorylation, as observed in the present study,
leading to arrhythmogenic increases in Ca^{2+} window cur-
rent.23,25 Phospholamban phosphorylation removes
phospholamban-induced SERCA inhibition, enhancing SR
Ca^{2+} uptake and improving cardiac relaxation and contra-
tion, whereas phospholamban dephosphorylation has op-
site effects, impairing diastolic and systolic function.10,22
Thus, both CaMKII hyperphosphorylation and phospholam-
bun hypophosphorylation are likely to be important contribu-
tors to the contractile failure we observed in ES rabbits.

Extensive work implicates CaMKII hyperphosphorylation
of RyR2 in arrhythmogenesis and defective Ca^{2+} han-
In a rabbit HF model, Ai et al. recently showed CaMKII activation and RyR hyperphosphorylation at both Ser2809 (PKA/CaMKII) and Ser2815 (CaMKII) sites. HF cardiomyocytes had enhanced SR Ca\(^{2+}\)/H\(_{11001}\) leak and reduced SR Ca\(^{2+}\)/H\(_{11001}\) load, which improved with CaMKII inhibition. CaMKII overexpression in rabbit cardiomyocytes also causes RyR2 hyperphosphorylation at both sites, as well as increased diastolic Ca\(^{2+}\)/H\(_{11001}\) spark frequency. There have been disagreements about which RyR2 phosphorylation site(s) (eg, Ser2809, Ser2815, and/or others) induces diastolic SR Ca\(^{2+}\) leak. In the present study, ES rabbits showed RyR2 hyperphosphorylation at both sites, whereas non-ES rabbits demonstrated Ser2815 hyperphosphorylation alone, potentially contributing to the arrhythmic phenotype and LV dysfunction in ES rabbits.

The effect of CaMKII on LTCCs has also been implicated in arrhythmogenesis. Recently, Koval et al. provided direct evidence that Ca\(_{v}\)1.2 β-subunits Thr498 and Leu493 are responsible for CaMKII actions to promote a high-activity Ca\(^{2+}\) channel gating mode (mode 2), Ca\(_{v}\)1.2 current facilitation, and early afterdepolarizations and that CaMKII actions at the β-subunit are sufficient to induce early afterdepolarizations in the absence of SR Ca\(^{2+}\) release. These findings, together with our results showing CaMKII activation and Ca\(_{v}\)1.2 hyperphosphorylation, suggest that LTCC reactivation might be a more central mechanism than RyR2 Ca\(^{2+}\) leak for ES in this model.

**Mechanism of Postshock VF Reinitiation**

Few studies have addressed mechanisms of postshock VF reinitiation. Zaugg et al. showed in Langendorff-perfused rat hearts that VF-induced [Ca\(^{2+}\)]\(_{i}\) overload causes failure of electric defibrillation and postshock VF reinitiation. Successful defibrillation led to a reduction in [Ca\(^{2+}\)]\(_{i}\) load. Incomplete reversal of [Ca\(^{2+}\)]\(_{i}\) overload after defibrillation was followed by spontaneous [Ca\(^{2+}\)]\(_{i}\) oscillations and VF reinitiation. Impaired SERCA function caused by phospholamban dephosphorylation impairs diastolic Ca\(^{2+}\) clearance from the cytosol and, along with diastolic Ca\(^{2+}\) releases from hyperphosphorylated RyRs, promotes diastolic [Ca\(^{2+}\)]\(_{i}\) overload. Another mechanism proposed by Ogawa et al. is that postshock APD abbreviation associated with unaltered [Ca\(^{2+}\)]\(_{i}\) transient duration enhances Na\(^{+}\)-Ca\(^{2+}\) exchanger currents, increasing the likelihood of afterdepolarizations that

![Figure 7](http://circ.ahajournals.org/lookup/doi/10.1161/CIRCULATIONAHA.111.042387)
model. Many studies have described CaMKII activation as a signal for proarrhythmia and myocardial dysfunction, but ours is the first to implicate Ca\(^{2+}\)/calmodulin/CaMKII signaling in ES pathophysiology. Not only was CaMKII hyperphosphorylation observed at functionally important CaMKII autophosphorylation, RyR2, and LTCC sites, but a therapeutic intervention targeting Ca\(^{2+}\)/calmodulin interaction demonstrated ES suppression and LV dysfunction improvement along with a reduction in CaMKII hyperphosphorylation. However, the phosphorylation abnormalities associated with ES were more complex than would be expected from CaMKII activation alone. The catalytic subunit of PKA was downregulated, and protein phosphatases (PP1 and PP2A) were upregulated, accounting for profound hypophosphorylation of phospholamban. The phosphorylation state of phospholamban determines its association with SERCA2a. Phospholamban dephosphorylation reduces SERCA2a function and, in combination with diastolic SR Ca\(^{2+}\) leak due to RyR2 hyperphosphorylation, would be expected to reduce SR Ca\(^{2+}\) stores and impair contractility, potentially accounting for the LV function impairment that we observed in ES rabbits. These observations may account for the tendency of ES to induce myocardial pump failure, which is the principal cause of excess mortality in ES patients.

Our results provide potential insights into the pathophysiology of ES. The initiating factors for ES are often cryptic, although psychological stress, acute myocardial ischemia, and electrolyte imbalances have all been implicated. We noted that repeated cycles of VF/defibrillation by themselves cause CaMKII hyperphosphorylation, a central component of CaMKII overactivity that favors arrhythmia occurrence and myocardial dysfunction. It is very possible that repeated VF/defibrillation cycles induce a positive-feedback cycle that enhances the probability of recurrent VF episodes and exacerbates contractile failure. This notion is supported by successful therapeutic effects of W-7.

Our findings also have potential implications for the clinical management of ES. Drug therapy of ES is problematic, with conventional antiarrhythmic agents providing little benefit and \(\beta\)-blockers and amiodarone seeming to be of the greatest value. Adrenergic receptor stimulation activates CaMKII; thus, antagonism of adrenergic activation of CaMKII may account for the beneficial actions of \(\beta\)-blockers and amiodarone. Our results also point to potential new approaches to treating and/or preventing ES. A Ca\(^{2+}\)/calmodulin interaction inhibitor (W-7) was highly effective in suppressing ES in our study. Interventions targeting the Ca\(^{2+}\)/calmodulin/CaMKII system may prove highly beneficial in preventing both further arrhythmic episodes and hemodynamic deterioration in ES patients.

Limitations

We focused on molecular changes underlying ES, performing detailed immunoblotting studies of Ca\(^{2+}\)-handling proteins in ES and non-ES rabbits. Because of the long preparation time and high mortality rates in this model, the number of available ES and non-ES rabbits was limited, and therefore we were unable to perform extensive functional studies of the reinduce VF. Recently, Wagner et al demonstrated that CaMKII differentially modulates K\(^{+}\) currents. Chronic CaMKII\(\delta\) overexpression in a transgenic mouse model prolonged APD by downregulating Kv4.2/KChIP2 and Kir2.1 responsible for \(I_{\text{to,fast}}\) and \(I_{\text{K1}}\), whereas acute CaMKII\(\delta\) overexpression shortened APD by enhancing \(I_{\text{K1}}\) and \(I_{\text{to,slow}}\) and accelerating \(I_{\text{to}}\) recovery in rabbit cardiomyocytes.

Novel Findings and Potential Significance

To our knowledge, this study is the first to report the molecular basis of ES in a clinically relevant chronic animal...
cellular mechanisms predicted to result from protein phosphorylation disturbances.

The precise mechanisms underlying the prominent phospholamban dephosphorylation observed in ES rabbits remain to be determined. Further studies on subcellular distribution of PP1 are needed to understand why phospholamban was dephosphorylated, a change opposite that seen for RyR2 and LTCC, which were hyperphosphorylated. Specific macromolecular compartmentalization of kinases, phosphatases, and target proteins is likely involved.

Long-term CAVB rabbits studied here had lower LV fractional shortening than at baseline, which is in contrast to a dog model of CAVB in which contractile function remains preserved. The ventricular rate decreases comparably, from \( \approx 280 \) bpm in sinus rhythm to 90 to 115 bpm in escape rhythm in rabbits versus from 4 to 50 bpm in dogs. The discrepancy in cardiac function response may be due to different species-dependent adaptation mechanisms or to greater spontaneous VT/VF occurrence in rabbits.

The detailed electrophysiological mechanisms underlying VF storm, particularly related to the relative roles of afterdepolarization-related triggered activity versus reentry, remain to be defined. These issues go beyond the scope of the present study. We corrected QT intervals by the Carlsson formula for rabbits, the validity of which was not tested under the bradycardic conditions of this study. We primarily examined LV tissue and function because LV function appears to be the principal factor associated with the occurrence and consequences of ES. We found that CaMKII activation, the central change involved in ES pathophysiology, occurs in the right ventricle as well as the LV, but we did not otherwise examine the right ventricle in detail.

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Disclosures

None.

References

CLINICAL PERSPECTIVE

Electrical storm (ES), characterized by recurrent ventricular tachycardia/fibrillation, is an increasing problem among implantable cardioverter-defibrillator patients. Despite acute cessation of ES with medical therapy and/or catheter ablation, the early mortality (within a few months of ES) is high and often nonsudden, involving progressive heart failure in particular. Underlying mechanisms are unknown. Defective Ca\(^{2+}\) handling is central to the pathogenesis of heart failure. Changes in phosphorylation of L-type Ca\(^{2+}\) channels, sarcoplasmic reticulum Ca\(^{2+}\)-release channel ryanodine receptors, and the sarcoplasmic reticulum Ca\(^{2+}\) uptake regulator protein phospholamban are linked to heart failure–related mechanical dysfunction and arrhythmogenic afterdepolarizations. To study the molecular basis of ES-related cardiac deterioration, we studied rabbits with chronic complete atrioventricular block equipped with implantable cardioverter-defibrillators. They developed QT prolongation and implantable cardioverter-defibrillator–detected ventricular fibrillation episodes, with ES (defined as clustered, frequently recurrent ventricular fibrillation episodes) occurring in \(50\%\). ES rabbits showed left ventricular function deterioration, along with striking activation of the Ca\(^{2+}\)-sensitive phosphorylating enzyme Ca\(^{2+}\)/calmodulin-dependent protein kinase II (CaMKII) and enhanced protein phosphatase expression. These alterations produced important changes in phosphorylation patterns, notably hyperphosphorylation of L-type Ca\(^{2+}\) channels and ryanodine receptors and dephosphorylation of phospholamban, which could explain arrhythmias and impaired contractility. Repeated ventricular fibrillation induction/defibrillation with implantable cardioverter-defibrillator shocks in control rabbits reproduced ES-related changes in CaMKII and phospholamban phosphorylation. Infusion of the calmodulin antagonist W-7 suppressed ventricular tachycardia/ventricular fibrillation episodes and rescued left ventricular dysfunction in ES rabbits, indicating a central pathophysiological role of CaMKII activation. These results strongly support the notion that CaMKII activation and Ca\(^{2+}\)-handling abnormalities resulting from ES events might be responsible for negative outcomes and suggest that interventions targeting the Ca\(^{2+}\)/calmodulin/CaMKII system might provide benefits in ES patients.
Ca\textsuperscript{2+}-Related Signaling and Protein Phosphorylation Abnormalities Play Central Roles in a New Experimental Model of Electrical Storm

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SUPPLEMENTAL MATERIAL
**Supplemental Figure Legends**

**Supplemental Figure 1.** Representative 2 episodes of non-sustained ventricular tachyarrhythmias (NSVT) detected and stored in ICDs. TdP-like VTs were detected as NSVTs.

**Supplemental Figure 2.** VF episodes were almost completely suppressed while the pacing rate was increased to 110 bpm. Multiple VF episodes developed again 1 day after the pacing rate back to 60 bpm at Day 48. This rabbit died at Day 50, with the last VF episode report showing VF-undersensing following 4 programmed therapies for repeated post-shock VF initiation.

**Supplemental Figure 3.** The daily number of VF-episodes in 2 ES-rabbits that had multiple VF-episodes early and transiently. VF-episodes occurred in a cluster in rabbit 2. Both rabbit 1 and 2 died of defibrillation failure during ES on Day 23 and Day 46, respectively.

**Supplemental Figure 4.** Top: Representative western blots of CaMKII-P and CaMKIIδ in RV tissue samples from 3 CTL, 3 non-ES and 3 ES-rabbits. Bottom: Mean±SEM band intensities in CTL (n=7), non-ES (n=5) and ES (n=5) rabbits. **P<0.01 versus CTL, †P<0.05 versus non-ES.

**Supplemental Figure 5.** A, Representative western blots of MyBP-C total, phospho-MyBP-C Ser282, Tn-I total, phospho-Tn-I Ser23/24, and phosphorylated MLC-2a. B, Mean±SEM band intensities and phosphorylation-fractions in CTL (n=5), non-ES (n=5) and ES (n=6) rabbits. *P<0.05 versus CTL.
Supplemental Figure 6. Top: Representative western blots for I-1, I-1 P67 and I-1 P35. Bottom: Mean±SEM I-1, I-1 P67 and I-1 P35 protein expression and phosphorylation-fraction in CTL (n=6), non-ES (n=5) and ES (n=6) rabbits.

Supplemental Figure 7. QTc (circles) and RR intervals (squares) during infusion in 5 ES-rabbits.
Supplemental Figure 2

The number of VF episode per day

Day 0 10 20 30 40 50

VVI pacing rate (bpm)

50 60 70 80 90 100 110 120