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Calpain-Dependent Cleavage of Junctophilin-2 and T-Tubule Remodeling in a Mouse Model of Reversible Heart Failure

Chia-Yen C. Wu, PhD; Biyi Chen, MD, PhD; Ya-Ping Jiang, MD; Zhiheng Jia, PhD; Dwight W. Martin, PhD; Shengnan Liu, BS; Emilia Entcheva, PhD; Long-Sheng Song, MD; Richard Z. Lin, MD

Background—A highly organized transverse tubule (T-tubule) network is necessary for efficient Ca²⁺-induced Ca²⁺ release and synchronized contraction of ventricular myocytes. Increasing evidence suggests that T-tubule remodeling due to junctophilin-2 (JP-2) downregulation plays a critical role in the progression of heart failure. However, the mechanisms underlying JP-2 dysregulation remain incompletely understood.

Methods and Results—A mouse model of reversible heart failure that is driven by conditional activation of the heterotrimeric G protein Gαq in cardiac myocytes was used in this study. Mice with activated Gαq exhibited disruption of the T-tubule network and defects in Ca²⁺ handling that culminated in heart failure compared with wild-type mice. Activation of Gαq/phospholipase Cβ signaling increased the activity of the Ca²⁺-dependent protease calpain, leading to the proteolytic cleavage of JP-2. A novel calpain cleavage fragment of JP-2 is detected only in hearts with constitutive Gαq signaling to phospholipase Cβ. Termination of the Gαq signal was followed by normalization of the JP-2 protein level, repair of the T-tubule network, improvements in Ca²⁺ handling, and reversal of heart failure. Treatment of mice with a calpain inhibitor prevented Gαq-dependent JP-2 cleavage, T-tubule disruption, and the development of heart failure.

Conclusions—Disruption of the T-tubule network in heart failure is a reversible process. Gαq-dependent activation of calpain and subsequent proteolysis of JP-2 appear to be the molecular mechanism that leads to T-tubule remodeling, Ca²⁺ handling dysfunction, and progression to heart failure in this mouse model. (J Am Heart Assoc. 2014;3:e000527 doi: 10.1161/JAHA.113.000527)

Key Words: Calpain • G protein • heart failure • junctophilin-2 • T-tubules

Heart failure is a major chronic illness in the United States, affecting an estimated 5.7 million Americans and presenting a great economic burden. Drugs used to block the progression of contractile deterioration of the failing heart include the angiotensin-converting enzyme inhibitors. However, current treatments for heart failure are highly unsatisfactory, and the morbidity and mortality from this disease remain high. Therefore, additional insights into the mechanisms that promote the progression of heart failure are urgently needed to provide additional targets for treating this disease.

Cardiac ventricular myocytes contain specialized structures called transverse tubules (T-tubules), which are regularly arrayed invaginations of the plasma membrane. The widely distributed T-tubule network allows rapid and synchronous activation of Ca²⁺ release from the sarcoplasmic reticulum (SR), which is essential for efficient excitation–contraction coupling. T-tubule integrity is thus an important determinant of cardiac function at the cell and organ levels. A number of studies have shown that loss and/or disorganization of T-tubules is part of the phenotypic change in failing hearts of human patients and animal models.

Although the exact molecular mechanisms that regulate T-tubule formation and maintenance in cardiac myocytes are still unclear, recent findings indicate that junctophilin-2 (JP-2) is a key regulator of T-tubule structure. The JP-2 protein is inserted into the outer membrane surface of the SR and spans the narrow space between T-tubules and the SR.
has been shown to be downregulated or mislocalized in all animal models of heart failure examined and in human heart failure patients.\textsuperscript{15,16,19–22} Ablation of JP-2 in cardiac myocytes in vitro and in vivo leads to a disrupted T-tubule network and abnormal Ca\textsuperscript{2+} handling.\textsuperscript{15,17,18} More recent studies suggested that microRNA-24 (miR-24) is a direct regulator of JP-2 homeostasis in the heart, and increased expression of miR-24 in failing hearts results in JP-2 downregulation.\textsuperscript{23–25} In addition to post-transcriptional regulation, it is yet not well understood how JP-2 is regulated at the post-translational level and how it becomes dysregulated by post-translational modification.\textsuperscript{25}

The heterotrimeric G protein G\textsubscript{q} plays a critical role in the development of cardiac hypertrophy and heart failure.\textsuperscript{26–28} For example, hormones such as angiotensin II and catecholamines that promote the progression of heart failure activate cell surface receptors that couple to G\textsubscript{q}. We previously showed that activation of G\textsubscript{q} in cardiac myocytes of adult mice rapidly leads to heart failure, but the contractile defect is reversed after G\textsubscript{q} signaling is turned off.\textsuperscript{29} However, the precise mechanism by which activation of G\textsubscript{q} promotes reversible heart failure remains unclear.

In this study, using a transgenic mouse model of inducible G\textsubscript{q} activity,\textsuperscript{30} we demonstrate that activation of G\textsubscript{q} caused JP-2 dysregulation, disruption of T-tubule ultrastructure, and abnormal Ca\textsuperscript{2+} release in cardiomyocytes. Strikingly, abrogation of excessive G\textsubscript{q} activation reversed all of these defects. We also identified a novel calpain cleavage fragment of JP-2 that is detected only in hearts with constitutive G\textsubscript{q} signaling to phospholipase C\beta (PLC\beta). Taken together, these data demonstrate that the mechanism by which G\textsubscript{q} induces reversible heart failure is through calpain-dependent cleavage of JP-2 protein and the associated T-tubule network.

**Methods**

**Materials**

Ryanodine receptor 2 (RyR2) antibody was obtained from Affinity Bioreagents. 4-[2-(6-diocetylamo)-2-naphthalenyl]ethenyl]-1-(3-sulfopropyl)-pyridinium (Di-8-ANEPPS), JP-2 antibody for immunostaining, goat anti-rabbit antibody conjugated to Alexa Fluor 488, and goat anti-mouse antibody conjugated to Alexa Fluor 647 were from Invitrogen. MM 4-64 gated to Alexa Fluor 488, and goat anti-mouse antibody conjugated to Alexa Fluor 647 were from Invitrogen. MM 4-64 for in situ T-tubule imaging was from AAT Bioquest. JP-2 antibody for Western blotting and immunoprecipitation was from Santa Cruz Biotechnology. Antibody to glyceraldehyde 3-phosphate dehydrogenase (GAPDH) was from Sigma-Aldrich. Calpain inhibitor III, also called MDL 28170, was from Bachem. Calpain-Mediated JP2 Cleavage in Heart Failure Wu et al.

**Animals**

Transgenic C57BL/6 mice expressing G\textsubscript{qQ209L-hbER} (referred to as QL) and G\textsubscript{qQ209L-hbER} with the R256A and T257A substitutions (referred to as AA) under the control of an \alpha myosin heavy chain promoter were described previously.\textsuperscript{30} The transgenic proteins are expressed in cardiac myocytes from birth. By fusing a mutant hormone-binding domain of the estrogen receptor (hbER)\textsuperscript{2} at the C-terminus of the transgenic proteins, they remain inactive until the mice are injected with tamoxifen. Mice 2 to 3 months of age were injected daily with 1 mg of tamoxifen suspended in peanut oil with or without 500 \mu g of calpain inhibitor III dissolved in DMSO. All animal-related experimental protocols for this study were approved by the Institutional Animal Care and Use Committee of Stony Brook University and the University of Iowa.

**Echocardiography**

Mice were anesthetized with 1% to 2% isoflurane, and transthoracic echocardiography was performed as previously described.\textsuperscript{32}

**T-tubule Visualization**

In situ T-tubule imaging and Fourier analysis of T-tubule integrity were performed as previously described.\textsuperscript{15} Peak power was measured as the absolute value using Gaussian fitting with Clampfit (Molecular Devices) as previously reported.\textsuperscript{15} Cardiac ventricular myocytes were isolated as described previously.\textsuperscript{33} T-tubule imaging, immunofluorescence confocal microscopy, and one-dimensional Fourier analysis on isolated cardiac ventricular myocytes were performed as previously described.\textsuperscript{16}

**Whole Heart Ca\textsuperscript{2+} Transient and Myocyte SR Ca\textsuperscript{2+} Content Measurements**

In situ Ca\textsuperscript{2+} imaging of physiologically coupled myocytes was performed in Langendorff-perfused intact hearts as previously described.\textsuperscript{34,35} SR Ca\textsuperscript{2+} content measurement in isolated myocytes in response to caffeine stimulation was performed as previously described.\textsuperscript{36}

**Western Blotting**

Mouse heart lysates were prepared in general lysis buffer (50 mmol/L HEPES, 2% Triton X-100, 50 mmol/L NaCl, 5 mmol/L EDTA, 50 mmol/L NaF, 10 mmol/L sodium pyrophosphate, 1 mmol/L sodium orthovandate, 0.5 mmol/L phenylmethylsulfonyl fluoride, and 10 \mu g/mL each of aprotinin and leupeptin, pH 7.5). After immunoblotting, signals were visualized using an ECL kit (PerkinElmer Life Sciences).
In-gel Digestion and Protein Identification

A frozen heart sample from a 2-month-old QL mouse injected with tamoxifen for 2 weeks was homogenized in general lysis buffer. Two samples (1 mg lysate protein) and immunoprecipitated product from 12 mg lysate protein) were diluted 1:1 in Bio-Rad 2x Laemmli sample buffer containing 5% 2-mercaptoethanol, heated 5 minutes at 95°C, and loaded into separate wells of a Bio-Rad Criterion Tris-HCl polyacrylamide gel (10% resolving gel and 4% stacking gel). After electrophoresis, the section of the gel containing the lysate lane was cut off and used for JP-2 immunoblotting. The remainder of the slab gel was stained with SYPRO Ruby Stain according to the manufacturer’s instructions. The images of the JP-2 immunoblot and the stained gel were aligned, and the regions corresponding to the immunostained bands were excised from the gel using a Bio-Rad Proteome-Works Plus Spot Cutter with a 1.5-mm cutting tip. The gel pieces were placed into wells of a 96-well plate, along with comparably sized pieces of blank regions of the gel that served as background references during sample processing. The excised gel pieces were destained, reduced, alkylated, and digested with trypsin (Promega Gold, Mass Spectrometry Grade). The resulting concentrated peptide extract was diluted into a solution of 2% acetonitrile (ACN), 0.1% formic acid (FA) (buffer A) for analysis. The peptide mixture was analyzed by automated microcapillary liquid chromatography–tandem mass spectrometry. Fused-silica capillaries (100-µm internal diameter) were pulled using a P-2000 CO2 laser puller (Sutter Instruments) to a 5-µm internal diameter tip and packed with 10 cm of 5-µm Magic C18 material (Agilent) using a pressure bomb. The column was then placed in-line with a Dionex Ultimate 3000 equipped with an autosampler. The column was equilibrated in buffer A, and the peptide mixture was loaded onto the column using the autosampler. The HPLC pump flowed at 100 µL/min, and the flow rate to the electrospray tip was reduced to ≈200 to 300 nL/min by a split. The HPLC separation was provided by a gradient between buffer A and buffer B (98% ACN, 0.1% FA). The HPLC gradient was held constant at 100% buffer A for 20 minutes after peptide loading followed by a 30-minute gradient to 40% buffer B. Then the gradient was switched from 40% to 80% buffer B over 3 minutes and held constant for 3 minutes. Finally, the gradient was changed from 80% buffer B to 100% buffer A over 1 minute and then held constant at 100% buffer A for 40 additional minutes. The application of a 1.8-kV distal voltage electrosprayed the eluted peptides directly into a Thermo Fisher Scientific LTQ XL ion trap mass spectrometer equipped with a nanoLC electrospray ionization source (ThermoFinnigan). Full mass spectra (MS) were recorded on the peptides over a 400- to 2000-m/z range, followed by five tandem mass (MS/MS) events sequentially generated in a data-dependent manner on the first, second, third, fourth, and fifth most intense ions selected from the full MS spectrum (at 35% collision energy). Mass spectrometer scan functions and HPLC solvent gradients were controlled by the Xcalibur data system (ThermoFinnigan).

MS/MS spectra were extracted from the RAW file with the use of Readw.exe (http://sourceforge.net/projects/sashimi). The resulting mzXML file contains all the data for all MS/MS spectra. The MS/MS data were searched with the use of Inspect37 against an IPI mouse database with optional modifications: +16 on methionine, +57 on cysteine, and +80 on threonine, serine, and tyrosine. Only peptides with a P≤0.01 value were analyzed further. Common contaminants (eg, keratins) were removed from the database. Proteins identified by at least 2 distinct peptides were accepted for a valid identification.

Calpain Activity Assay

Calpain activity was assayed using the BioVision Calpain Activity Assay kit. Heart tissue was homogenized in the extraction buffer supplied with the kit, incubated on ice for 20 minutes, and then centrifuged at 10 000g at 4°C. Then, 50 µg of protein in the supernatant was diluted in the extraction buffer and mixed with reaction buffer and calpain substrate. Samples were incubated at 37°C, and readings were taken every 400 seconds for 1 hour in a microplate fluorescence reader (excitation of 360 nm and emission of 520 nm).

Statistics

Data were expressed as mean±SEM. The Student t test was used for analysis of T-tubule peak power (Figure 5B), JP2 power spectra (Figure 6B), and JP-2/RyR2 colocalization (Figure 6C). All Western blot data (Figures 7A and 10A, 10B) and calpain activity assay (Figure 9A) were analyzed by using Mann–Whitney U test or Kruskal–Wallis test; one-way ANOVA with Bonferroni post-test was used to analyze T-tubule peak power (Figure 11B) and JP-2/RyR2 colocalization (Figure 11C); and linear mixed-effects models test was used for analysis of Ca2+ transient parameters (Figures 2B, 2D and 3B, 3C) and TTpower (Figure 4B) from intact hearts. The Pearson correlation statistics was used in Figure 6C to assess correlation between groups. Statistical analysis was carried out using SPSS V 15.0, and P<0.05 was considered statistically significant.

Results

Reversibility of Gαq-Induced Heart Failure

In a previous study, we showed that transgenic mice expressing the GαqQ209L-hbER protein (abbreviated as QL mice hereafter)
rapidly developed decompensated heart failure when injected with tamoxifen to activate Gαq signaling. In this study, we sought to better understand the molecular mechanisms of heart failure development induced by Gαq activation in this animal model. We first demonstrated the reversibility of heart failure in the QL mice by performing serial echocardiographic examinations of wild-type (WT) and QL mice before tamoxifen injection (“Baseline”), after 2 weeks of daily injections (“Tamoxifen”), and 3 weeks after the last drug injection (“Recovery”). Shown in Figure 1A are M-mode echocardiograms obtained from 1 representative WT and 1 representative QL animal at the 3 treatment stages. Before tamoxifen injection, the QL mice had normal cardiac contractility as measured by fractional shortening (Figure 1B). Two weeks of tamoxifen injections induced dramatic decreases in fractional shortening in all of the QL mice but did not have significant negative effects on the WT mice (Figure 1B). Three weeks after the cessation of tamoxifen injections, cardiac contractility in all of the QL mice recovered to baseline levels (Figure 1B). The QL mice also developed a substantial increase in left ventricular volume that improved during the recovery period, as shown in Figure 1B. Tamoxifen did not increase the left ventricular

![Figure 1](http://jaha.ahajournals.org/)
Table 1. Echocardiographic Measurements of Mice Injected for 2 Weeks

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Tamoxifen</th>
<th>Tamoxifen+Calpain Inhibitor</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WT  QL AA</td>
<td>WT  QL AA</td>
<td>QL WT QL</td>
<td></td>
</tr>
<tr>
<td>LVEDD, mm</td>
<td>3.28±0.05 3.07±0.03  3.61±0.03</td>
<td>3.38±0.06 3.97±0.06*  3.60±0.03</td>
<td>3.43±0.04† 3.30±0.05  3.25±0.04‡</td>
<td></td>
</tr>
<tr>
<td>LVEDD, mm</td>
<td>1.8±0.06 1.62±0.03  1.77±0.03</td>
<td>1.75±0.05 3.16±0.07*  1.70±0.03</td>
<td>1.89±0.04† 1.76±0.05  1.73±0.03‡</td>
<td></td>
</tr>
<tr>
<td>PWT, mm</td>
<td>0.97±0.03 0.91±0.02  0.80±0.02</td>
<td>1.00±0.03 0.82±0.03*  0.86±0.03</td>
<td>0.73±0.03 0.91±0.03  1.00±0.03‡</td>
<td></td>
</tr>
<tr>
<td>FS, %</td>
<td>46.6±1.5 47.3±0.8   50.9±0.64</td>
<td>46.5±1.3 20.9±1.3*  52.8±0.43</td>
<td>45.4±0.8† 46.7±1.3  47.6±1.1†</td>
<td></td>
</tr>
<tr>
<td>HR, bpm</td>
<td>523.9±18.2 500.6±27.1</td>
<td>454.6±2.36 487.7±6.1  262.2±23.6*</td>
<td>448.2±3.53 370.6±17.0† 557.5±13.7 551.0±11.1†</td>
<td></td>
</tr>
</tbody>
</table>

Values are means±SEM. Serial echocardiographic examinations were done on 5 WT and 7 QL mice at the 3 treatment stages (Baseline, Tamoxifen, and Recovery). A separate group of QL mice (n=7) was examined after 2 weeks of daily injections with tamoxifen plus calpain inhibitor. Three AA mice were also studied before and after tamoxifen injection. bpm indicates beats per minute; FS, fractional shortening; HR, heart rates; LVEDD, left ventricular end-diastolic diameter; LVESD, left ventricular end-systolic diameter; PWT, posterior wall thickness; WT, wild-type.

volume of WT mice (Figure 1B). Table 1 summarizes the serial echocardiographic data from both groups of mice. It should be noted that when QL mice died during the 2 weeks of tamoxifen injections, as we previously reported,30 the data from those animals were not included in the study.

We performed additional experiments with WT and QL mice that were injected with tamoxifen for only 1 week. At this time point, the contractile abnormality of the QL mice as measured by echocardiography was not as severe as that observed after 2 weeks of injections (Table 2). Figure 1C summarizes the contractile changes of QL mice under the various conditions. The cardiac contractility of QL mice injected for 1 week with tamoxifen was decreased by 37% compared with the WT group, whereas the contractility of QL mice injected for 2 weeks was reduced by 55%. These data indicate that tamoxifen-induced activation of Goq signaling causes a progressive reduction in cardiac contractile function.

Table 2. Echocardiographic Measurements of Mice Injected With Tamoxifen for 1 Week

<table>
<thead>
<tr>
<th></th>
<th>Basal</th>
<th>Tamoxifen 1 Week</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WT  QL</td>
<td>WT  QL</td>
</tr>
<tr>
<td>LVEDD, mm</td>
<td>3.31±0.05 3.55±0.08</td>
<td>3.62±0.05 3.74±0.07</td>
</tr>
<tr>
<td>LVESD, mm</td>
<td>1.68±0.03 1.74±0.07</td>
<td>1.69±0.03 2.56±0.07*</td>
</tr>
<tr>
<td>PWT, mm</td>
<td>0.75±0.02 0.74±0.03</td>
<td>0.71±0.02 0.83±0.04</td>
</tr>
<tr>
<td>FS, %</td>
<td>49.1±0.9 50.7±1.54</td>
<td>50.6±0.93 31.8±1.89*</td>
</tr>
<tr>
<td>HR, bpm</td>
<td>486.2±25.2 464.3±9.6</td>
<td>447.0±8.9 333.5±40.0*</td>
</tr>
</tbody>
</table>

Values are mean±SEM. Serial echocardiographic examinations were done on 3 WT and 3 QL mice at the 2 treatment stages (Basal and Tamoxifen 1 week); WT indicates wild-type; LVEDD, left ventricular end-diastolic diameter; LVESD, left ventricular end-systolic diameter; PWT, posterior wall thickness; FS, fractional shortening; HR, heart rates; bpm, beats per minute.

*P<0.01; compared with WT-tamoxifen.

Abnormal Ca2+ Handling in Goq-induced Heart Failure

Heart failure is often associated with defective Ca2+ handling in myocytes.38 To investigate Ca2+ handling in QL mice with heart failure, in situ imaging of Ca2+ transients was performed in intact WT and QL hearts after 1 or 2 weeks of tamoxifen injections and in QL hearts after 3 weeks of recovery. Figure 2A shows representative Ca2+ transient images obtained from spontaneously beating hearts, and Figure 2C shows images obtained from hearts paced at 5 Hz. Note that the spontaneous rate of the QL-tamoxifen heart was slower than that of the WT-tamoxifen heart (Figure 2A; also see Tables 1 and 2). Ca2+ transient amplitude in hearts from QL mice treated with tamoxifen for 1 week was significantly reduced compared with the WT-tamoxifen group (Figure 2B and 2D). The reduction in Ca2+ transient amplitude was more severe in QL mice injected for 2 weeks (Figure 2B and 2D). This defect...
was completely reversed in the QL-recovery hearts (Figure 2B and 2D). In addition, the time needed to reach peak Ca$^{2+}$ amplitude ($T_{\text{peak}}$) was markedly increased in spontaneously beating or paced QL-tamoxifen hearts, and this alteration was also completely reversed in the QL-recovery hearts (Figure 2B and 2D). Again, this defect was more severe in QL mice injected with tamoxifen for 2 weeks than in mice injected for 1 week (Figure 2B). The time from peak to 50% decay of the Ca$^{2+}$ signal ($T_{50}$) was also significantly longer in spontaneously beating QL hearts from mice injected for 2 weeks, but not for 1 week, compared with WT (Figure 2B). However, this difference was eliminated when the WT and QL hearts were paced at the same rate (5 Hz), suggesting that the decelerated decay of Ca$^{2+}$ transients is frequency dependent (Figure 2D).

Similar to what we found in the whole heart, isolated QL-tamoxifen myocytes paced at either 1 Hz or 3 Hz also exhibited a marked decrease in Ca$^{2+}$ transient amplitude, an increase in $T_{\text{peak}}$, and no significant difference in $T_{50}$ compared with WT-tamoxifen cells (Figure 3A and 3B). We next investigated whether a decrease in SR Ca$^{2+}$ content might account for the defect in Ca$^{2+}$ handling caused by activation of $\Gamma_G\alpha_q$. Isolated myocytes were paced at 1 Hz and then treated with caffeine to release the SR store Ca$^{2+}$. The amplitude of caffeine-induced Ca$^{2+}$ release from the SR was minimally affected in the QL-tamoxifen versus the WT-tamoxifen myocytes (Figure 3C and 3D).

$\Gamma_G\alpha_q$ activates PLC$\beta$ to generate diacylglycerol and inositol trisphosphate (IP$_3$), 2 second messengers that cause an increase in protein kinase C activity and Ca$^{2+}$ release, respectively.\textsuperscript{39} We previously generated transgenic mice with cardiac myocyte-specific expression of a $\Gamma_G\alpha_q$ Q209L-hbER protein with alanine substitutions at amino acids Arg256 and Thr257.\textsuperscript{30} This mutant (referred to as AA) cannot activate PLC$\beta$.\textsuperscript{30} Calcium transient parameters in hearts of tamoxifen-

![Figure 2. Decreased amplitude and slowed kinetics of Ca$^{2+}$ transients in QL hearts. Ca$^{2+}$ transients were imaged in situ in hearts prepared from tamoxifen-treated WT, QL (1 or 2 weeks), and AA mice and from QL mice 3 weeks after the last tamoxifen injection (QL-recovery). A, Representative images of Ca$^{2+}$ transients in spontaneously beating hearts. B, Summary of Ca$^{2+}$ transient parameters derived from data collected as in (A): amplitude ($F/F_0$), time to peak ($T_{\text{peak}}$), and time from peak to 50% decay ($T_{50}$). **$P<0.01$ compared with WT-tamoxifen; *$P<0.05$ compared with QL-tamoxifen 2 weeks by linear mixed-effects models test. C, Representative images of external stimulation (5 Hz)–triggered Ca$^{2+}$ transients. D, Summary of Ca$^{2+}$ transient parameters derived from data collected as in (C). **$P<0.01$ compared with WT-tamoxifen; *$P<0.05$ compared with QL-tamoxifen 2 weeks by linear mixed-effects models test, mean±SEM, n=223 cells for WT, n=201 cells for QL 1 week, n=280 cells for QL 2 weeks,: n=288 cells for QL-Rec from 3 hearts for each group, respectively. WT indicates wild-type.](http://jaha.ahajournals.org/)

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injected AA mice were similar to those of the WT-tamoxifen hearts (Figure 2). Echocardiographic examination of AA mice before and after 2 weeks of tamoxifen injections showed that fractional shortening and other left ventricular measurements did not change significantly (Figure 1 and Table 1). These results indicate that activation of PLCβ is required for the development of heart failure in QL mice.

Reversible T-tubule Disruption

T-tubule structure is an important determinant of cardiac excitation–contraction coupling function. To determine whether T-tubule remodeling occurs in QL mice with heart failure, we mounted hearts on a Langendorff apparatus, perfused them with a lipophilic dye (MM 4-64; AAT Bioquest) that stains the plasma membrane, and used in situ confocal imaging to visualize T-tubules in left ventricular epicardial myocytes of the intact hearts. Figure 4A shows representative images of WT and QL hearts. When compared with WT-tamoxifen hearts, myocytes in hearts of the QL mice injected with tamoxifen for 1 week exhibited a slightly disorganized pattern of T-tubules, with a statistically significant decrease in power at the dominant frequency as analyzed by two-dimensional Fourier transform (Figure 4A and 4B). However, after 2 weeks of tamoxifen treatment, the T-tubule network of QL myocytes exhibited markedly disorganized pattern, giving rise to an overall chaotic appearance of the T-tubule network and, hence, low spatial periodicity. Power spectrum analysis using two-dimensional Fourier transform yielded much lower power at the dominant frequency in the 2-week QL-tamoxifen group (Figure 4A and 4B). This defect was almost completely reversed in the hearts of QL mice after 3 weeks of recovery (Figure 4A and 4B). Additional histogram analysis of the images showed that most of the images in the tamoxifen-treated WT group had highly organized T-tubules whose TTpower fell in the 2.0 to 2.6 range, whereas the majority of 2-week QL-tamoxifen cells exhibited power of <1.7 (Figure 4C) and most of the 1-week QL-tamoxifen myocytes exhibited TTpower that fell between those for 2-week QL-tamoxifen and WT-tamoxifen cells (Figure 4C). Although T-tubules in most of the QL-recovery myocytes were highly organized with TTpower of >2.0, some of them still had disrupted T-tubules whose TTpower fell into the 1.4 to 1.7 bin range (Figure 4C). Data from additional T-tubule imaging experiments using isolated myocytes (Figure 5) are consistent with those obtained using in situ imaging from intact hearts. In

**Figure 2.** Continued.
contrast to QL-tamoxifen myocytes, myocytes from AA-tamoxifen mice exhibited an organized T-tubule pattern (Figure 5C). Taken together, our data indicate that Gaq activation of PLCβ is the mechanism that causes T-tubule disruption in QL hearts.

JP-2 Abnormalities Due to Activation of Gaq

JP-2 plays a critical role in regulating T-tubule organization in cardiac myocytes. We recently reported that genetic ablation of 2 phosphoinositide 3-kinases in cardiac myocytes led to decompensated heart failure in mice and altered localization of JP-2 with no change in protein expression. Therefore, we used immunofluorescence microscopy to determine whether JP-2 is also mislocalized in myocytes of QL mice with heart failure. As expected, staining of JP-2 in cardiomyocytes from tamoxifen-injected WT mice showed an orderly striated pattern that strongly overlapped with RyR staining (Figure 6A). In contrast, JP-2 in QL-tamoxifen myocytes did not show a striated distribution with a constant periodic spacing (Figure 6A). The lack of periodicity was reflected by the low normalized power calculated from the one-dimensional Fourier transform of the staining signal (Figure 6B). JP-2 colocalization with RyR was also reduced in the QL-tamoxifen myocytes (Figure 6C). The striated arrangement of JP-2 and JP-2 colocalization with RyR were...
restored in the QL myocytes after 3 weeks of recovery (Figure 6).

Western blotting showed that there was a marked decrease in the level of full-length JP-2 in heart lysates of QL-tamoxifen mice compared with WT-tamoxifen animals (Figure 7A and 7B). Interestingly, a cleaved form of JP-2 was detected in the QL-tamoxifen hearts (Figure 7A). This JP-2 cleavage product was also seen in hearts of QL mice collected after only 7 days of tamoxifen injections (Figure 7A). At this time point, the level of full-length protein was not reduced in the QL hearts, suggesting a compensatory response to increased cleavage of JP-2 (Figure 7A). In contrast, tamoxifen injection of AA mice for 2 weeks did not cause a decrease in the expression of JP-2 or induce the cleaved form of this protein in heart lysates (Figure 7B). The expression level of full-length JP-2 in QL hearts returned to WT levels after 3 weeks of recovery from the tamoxifen injections, and the cleaved form of JP-2 was no longer detected (Figure 7A).

Figure 4. Disruption of the T-tubule network in QL hearts. A, In situ imaging of T-tubules in the left ventricle of intact WT-tamoxifen, QL-tamoxifen (1 or 2 weeks), and QL-recovery hearts perfused with MM 4-64. Representative power spectrum of spatial frequency for each group was shown next to the T-tubule images. B, T-tubule organization was analyzed by two-dimensional Fourier transform of the MM 4-64 image to calculate the strength of T-tubule regularity (TT-power). **P<0.01 vs WT, ##P<0.01 vs QL 2 weeks by linear mixed-effects models test, mean±SEM, n=75 images, 5 hearts for WT, n=45 images, 3 hearts for QL 1 week, n=90 images, 6 hearts for QL 2 weeks, respectively. C, Histogram distribution of TT-power from individual frame of T-tubule images from left ventricles. WT indicates wild-type.
Taken together, these results indicate that JP-2 protein localization and expression are both altered during the development of Gαq-induced heart failure. Furthermore, the JP-2 abnormality is a reversible process. Our data also suggest that PLCβ activation is required for Gαq-induced JP2 cleavage.

Figure 5. Disruption of the T-tubule network in single QL cardiomyocytes. A, Representative confocal microscopy images of cardiac myocytes isolated from untreated WT and QL mice (Baseline), mice injected for 2 weeks with tamoxifen (Tamoxifen), and mice allowed to recover for 3 weeks after the last tamoxifen injection (Recovery). Myocytes were stained with di-8-ANEPPS. Phase contrast images of the same cells are displayed in the bottom panels. Scale bars are 10 μm. The insets show ×2 magnified views. B, Normalized peak power (at the dominant frequency) computed from one-dimensional Fourier analysis of the di-8-ANEPPS signal as a measure of T-tubule spatial organization. Data are mean±SEM (n=16 to 27 cells from ≥3 hearts per group; *P<0.01, Student’s t test). C, Representative confocal microscopy images of cardiac myocytes isolated from 3 AA mice treated with tamoxifen for 2 weeks. Myocytes were stained with di-8-ANEPPS. WT indicates wild-type.
**Figure 6.** Mislocalization of JP-2 in QL myocytes. A, Representative immunofluorescence confocal microscopy images of myocytes prepared from WT and QL mice after 2 weeks of tamoxifen treatment (Tamoxifen) or 3 weeks after the last tamoxifen injection (Recovery). Cells were colabeled with antibodies against JP-2 (green) and RyR (red). Scale bars are 10 μm. B, Normalized power spectra calculated from one-dimensional Fourier transform of the JP-2 signal to analyze its spatial organization. Data are mean±SEM (⁎P<0.01, Student’s t test; n=19 WT-tamoxifen cells; n=32 QL-tamoxifen cells; n=14 WT-recovery cells; n=18 QL-recovery cells; ≥3 hearts per group). C, Pearson’s coefficient for colocalization of JP-2 and RyR. Data are mean±SEM (⁎P<0.01, Student’s t test; n=19 WT-tamoxifen cells; n=29 QL-tamoxifen cells; n=13 WT-recovery cells; n=14 QL-recovery cells; ≥3 hearts per group). JP-2 indicates junctophilin-2; WT, wild-type.
Activation of Calpain and Cleavage of JP-2

To further investigate the mechanism by which \( \Gamma_{Gq} \) induces JP-2 cleavage, we used proteomics to analyze the JP-2 protein in the QL heart after 2 weeks of tamoxifen injections. JP-2 proteins were immunoprecipitated from heart lysates and then resolved by SDS-PAGE. Full-length and cleaved forms of JP-2 were cut out of the gel and digested with trypsin. Analysis of the tryptic peptides by mass spectroscopy revealed a unique polypeptide in the sample of cleaved JP-2 whose amino-terminal leucine is not adjacent to a trypsin cleavage site (Figure 8A and 8B, sequence in red). The cleavage site at the amino terminus of this peptide is a potential calpain recognition site. No JP-2 peptides amino-terminal to this site were identified in the sample of cleaved JP-2, whereas such peptides were readily detected in the sample of full-length JP-2 (Figure 8B).

To further investigate the role of calpain in JP-2 cleavage, we measured calpain activity in heart lysates prepared from mice injected with tamoxifen. We found that the average calpain activity was 2-fold higher in QL hearts than in WT hearts after 1 week of injections and, after 2 weeks of treatment calpain activity in QL hearts, was \( >2 \) -fold higher than in the corresponding WT group (Figure 9A). Consistent with the increase in calpain activity, we detected a significant increase in the cleaved form of \( \alpha \)-fodrin, a previously known calpain cleavage substrate, in QL hearts (Figure 9B). In contrast, AA hearts, did not have higher calpain activity than WT hearts (Figure 9A). Western blots of heart lysates showed that the amount of calpain 1 protein in QL-tamoxifen samples was lower than in WT-tamoxifen or AA-tamoxifen samples, indicating that the increase in activity must be due to QL-dependent activation of the enzyme (Figure 10A). We also analyzed the heart samples by western blotting for calpastatin and did not detect a significant change in levels upon activation of \( \Gamma_{Gq} \) (Figure 10B).

Next, we injected QL mice for 2 weeks with calpain inhibitor III (reported to be selective for calpains I and II) together with tamoxifen and found that cleavage of JP-2 was almost completely blocked in the calpain inhibitor-treated mice (Figure 11A). The inhibitor also protected myocytes from the deleterious effects of \( \Gamma_{Gq} \) activation on T-tubule organization and JP-2 and RyR colocalization (Figure 11B and 11C). Importantly, cardiac contractile function was also protected in QL mice treated with tamoxifen plus the calpain inhibitor (Table 1). Taken together, these results strongly suggest that activation of calpain by \( \Gamma_{Gq} \) leads to cleavage of JP-2 in cardiac myocytes, resulting in T-tubule disruption, \( Ca^{2+} \) handling dysfunction, and then heart failure.
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The development of acute heart failure,\textsuperscript{17} in particular, this phenotype was observed despite suboptimal JP2 silencing in adult hearts, which was rescued by cardiac specific overexpression of JP2.\textsuperscript{12} Although there are other mechanisms that contribute to the heart failure phenotype (as discussed next), these previous reports support the notion that the signaling cascade of JP2 downregulation  \(\rightarrow\) T-tubule remodeling  \(\rightarrow\) Ca\textsuperscript{2+} handling dysfunction constitutes an important mechanism responsible for cardiac contractile failure in heart disease. Until now, the mechanisms underlying JP2 dysregulation in heart failure remained incompletely understood.

In this study, using a mouse model of Gx-q-dependent reversible heart failure, we provide compelling evidence that turning on Gx-q induces calpain activation, JP2 cleavage (at the site of L201-L202), T-tubule disruption, and heart failure. On the contrary, turning off Gx-q reverses all of these events. Moreover, treatment of mice with a calpain inhibitor prevents Gx-q-dependent JP2 cleavage, T-tubule disruption, and the development of heart failure. Thus, our data establish that Gx-q-dependent activation of calpain and subsequent calpain-dependent proteolysis of JP2

**Figure 8.** Proteomics analysis to determine the cleavage site in JP2 from QL hearts. A, Proteomics analysis identified a unique tryptic peptide in the sample of cleaved JP2 from QL-tamoxifen 2-week hearts. The amino terminus was potentially generated by cleavage by the calcium-dependent protease calpain. B, Full-length and cleaved forms of JP2 were immunoprecipitated from QL-tamoxifen hearts, purified by SDS-PAGE, and digested with trypsin. Peptides in both samples were identified by mass spectroscopy. In blue are peptides identified in each preparation. In red is the peptide identified in the cleaved JP2 sample that does not have a trypsin cleavage site next to the amino terminal leucine. JP2 indicates junctophilin-2.

**Discussion**

Studies from many groups have provided compelling evidence that T-tubule remodeling is a common pathological alteration in failing myocytes of almost all origins, including different animal heart failure models of different species and etiologies and human heart failure patients with different cardiac etiologies (see Table 1 of ref. [40]). It is now also clear that T-tubule remodeling is not a secondary modification after heart failure but rather an important early ultrastructural alteration that contributes to the development of heart failure.\textsuperscript{15} Disruption of this myocyte ultrastructure causes abnormalities of Ca\textsuperscript{2+} handling such as dyssynchrony and reduction of SR Ca\textsuperscript{2+} release, leading to myocyte contractile dysfunction and development of heart failure in various heart diseases.\textsuperscript{5,8,10,11,15,16,44–46} More recent studies suggested that JP2 downregulation is a key mechanism underlying T-tubule alterations in heart failure.\textsuperscript{15,17} JP2 expression levels are reduced in failing hearts,\textsuperscript{15,16,19–22} and acute genetic knockdown of JP2 by approximately 50% to 60% in cardiomyocytes in adult mice leads to T-tubule disorganization\textsuperscript{15,17} and the development of acute heart failure.\textsuperscript{17} In this study, using a mouse model of Gx-q-dependent reversible heart failure, we provide compelling evidence that turning on Gx-q induces calpain activation, JP2 cleavage (at the site of L201-L202), T-tubule disruption, and heart failure. On the contrary, turning off Gx-q reverses all of these events. Moreover, treatment of mice with a calpain inhibitor prevents Gx-q-dependent JP2 cleavage, T-tubule disruption, and the development of heart failure. Thus, our data establish that Gx-q-dependent activation of calpain and subsequent calpain-dependent proteolysis of JP2

**B**

Full length JP-2

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001 MSGRFDFFDGAGCGEWEKGAGHKHLCTGPQGGEYSGSNMGEFVAGEO
051 VYTIPSNTFGYWSQGKRHLGIIIETGWRNYGGKFGFGVYGRQST
101 N5GAKYETMNGLQDGYTEADGTYYQUFNMGHRHGVRVQSVPGY
151 RAVVYNPLRTLSSRSLRSGHNNORMLSGGQSPPPRGGFAFLT
201 LALATAEARPPQGLTITGTLGLRRLRSERTSTLGSQSSRLFSKLSESLSGA
251 SDAOASTGSLAEAGEDPDAAPFDADIDAATTTEYMGWKNKDREGFGGSY
301 EISSSLRYEGELNLVENLNYGYYKEGKRNVLKVRRLP
351 LKSSKVRQKVKEHYGEAQARAAAIARQKAEIAASRTSHTAKAAEAQEAAL
401 AAANQIESNIALAKELAPDPFFQGPFEYQKRLQEEEIENSESLAPPERRG
451 IPTQPQGGPSPAPQTKRPRAAGDQGKDGOLL
501 SPSWNGEPEGGESRGAPATPSOARGRRSPARPASEHEMIAELQPPAPQSE
551 PENVAMNYSYVARTGEPFPPEEPLEDGEEPEPEPEPEVRENSAPPSVY
601 ATVPEEPFSPPVPAKATLQEPFIVPKEAPKAKAKARTEALGKSAAGA
651 KKKGRKEVAQAKEEVEEVE EVNPVTLCIMVINILNIGAILFVHLLT*"```

Cleaved form of JP-2

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001 MSGRFDFFDGAGCGEWEKGAGHKHLCTGPQGGEYSGSNMGEFVAGEO
051 VYTIPSNTFGYWSQGKRHLGIIIETGWRNYGGKFGFGVYGRQST
101 N5GAKYETMNGLQDGYTEADGTYYQUFNMGHRHGVRVQSVPGY
151 RAVVYNPLRTLSSRSLRSGHNNORMLSGGQSPPPRGGFAFLT
201 LALATAEARPPQGLTITGTLGLRRLRSERTSTLGSQSSRLFSKLSESLSGA
251 SDAOASTGSLAEAGEDPDAAPFDADIDAATTTEYMGWKNKDREGFGGSY
301 EISSSLRYEGELNLVENLNYGYYKEGKRNVLKVRRLP
351 LKSSKVRQKVKEHYGEAQARAAAIARQKAEIAASRTSHTAKAAEAQEAAL
401 AAANQIESNIALAKELAPDPFFQGPFEYQKRLQEEEIENSESLAPPERRG
451 IPTQPQGGPSPAPQTKRPRAAGDQGKDGOLL
501 SPSWNGEPEGGESRGAPATPSOARGRRSPARPASEHEMIAELQPPAPQSE
551 PENVAMNYSYVARTGEPFPPEEPLEDGEEPEPEPEPEVRENSAPPSVY
601 ATVPEEPFSPPVPAKATLQEPFIVPKEAPKAKAKARTEALGKSAAGA
651 KKKGRKEVAQAKEEVEEVE EVNPVTLCIMVINILNIGAILFVHLLT*"```
are important molecular mechanisms that contribute to T-tubule remodeling, Ca\(^{2+}\) handling dysfunction, and progression to heart failure in this mouse model. Our data revealed a post-translational mechanism—calpain-mediated JP-2 proteolysis—involved in JP-2 dysregulation in heart failure. This finding is complementary to miR-24–mediated post-transcriptional regulation of JP-2 expression, as recently discovered by Wang and his colleagues,\(^{23-25}\) and microtubule-mediated defects in JP-2 trafficking that also contribute to T-tubule remodeling and the development of heart failure.\(^{47}\)

Many studies have implicated β-adrenergic and angiotensin II G protein–coupled receptor signaling in Ca\(^{2+}\)-mediated calpain activation in failing hearts.\(^{48,49}\) Because we use a model of constitutive G\(_{q}\) signaling, we speculate that the mechanism of calpain activation is similar to that reported in previous studies (ie, through a common mechanism of Ca\(^{2+}\) elevation). Active G\(_{q}\) binds and stimulates PLCβ to produce diacylglycerol and IP\(_{3}\) from phosphatidylinositol-4,5-bisphosphate.\(^{39}\) IP\(_{3}\) binds to IP\(_{3}\) receptors (IP\(_{3}\)Rs) to stimulate the release of Ca\(^{2+}\) from the endoplasmic reticulum or the nuclear envelope.\(^{50}\) Our results using the AA mouse strain indicate activation of PLCβ is required to activate calpain to cleave JP-2. Multiple pieces of evidence indicate that enhancement of IP\(_{3}\)–IP\(_{3}\)R signaling alters cardiac excitation-contraction coupling; that is, it increases the systolic global Ca\(^{2+}\) transient and elevates the diastolic Ca\(^{2+}\) level.\(^{51-53}\) Based on the results from our study, one may surmise that G\(_{q}\)-induced IP\(_{3}\) mediated Ca\(^{2+}\) release that could lead to activation of calpain, which then cleaves JP-2 to cause the observed phenotype. However, our results do not rule out the possibility that PLCβ could be regulating calpain through a protein kinase C pathway. Future studies that determine the downstream signaling events after PLCβ activation will provide new mechanistic information to fill this gap in knowledge. In addition, studies are needed to characterize the intracellular location(s) where JP-2 is cleaved by activated calpain.

It is also unclear why calpain activity is increased despite a decrease in expression of calpain I. Regulation of calpain activity is complex and not completely understood. We speculate that the decrease in calpain I expression is a compensatory response by the myocytes to turn off the deleterious effects of calpain activation. Downexpression of calpastatin, the endogenous calpain inhibitor, is also not responsible for the increased calpain activity. We postulate that changes in calpain localization, which have been
Figure 11. Inhibition of JP-2 cleavage in QL hearts by a calpain inhibitor. WT and QL mice were injected daily with tamoxifen (1 mg) plus or minus calpain inhibitor III (500 μg) for 2 weeks. A, Heart lysates were analyzed by western blotting for JP-2. The blot was reprobed for GAPDH as a loading control. B, Ventricular myocytes were isolated and stained with di-8-ANEPPS for the T-tubule structure. Representative confocal microscopy images are shown. Scale bars are 10 μm. The bar graph shows normalized peak power (at the dominant frequency) computed from one-dimensional Fourier analysis of the di-8-ANEPPS signal as a measure of T-tubule spatial organization. Data are mean±SEM (*P<0.01, one-way ANOVA with Bonferroni post test; n=22 to 27 cells from ≥3 hearts per group). C, Ventricular myocytes were isolated and stained with antibody against JP-2 and RyR. Representative immunofluorescence confocal microscopy images are shown. Scale bars are 10 μm. The bar graph shows normalized peak power of the JP-2 signal to analyze its spatial organization. The bottom bar graph shows the Pearson’s coefficient of JP-2/RyR colocalization. Data are mean±SEM (*P<0.01, one-way ANOVA with Bonferroni post-test; n=16 to 29 cells from ≥3 hearts per group). GAPDH indicates glyceraldehyde 3-phosphate dehydrogenase; JP-2, junctophilin-2; WT, wild-type.
associated with differential calpain activity,\textsuperscript{44,45} may be responsible for the increase in calpain activity. Imaging studies that examine the cellular location of calpain isoforms in isolated myocytes following acute activation of G\textsubscript{xq} could be informative.

The mechanisms by which withdrawal of tamoxifen restores cardiac function remain incompletely elucidated. We have previously reported that withdrawal of tamoxifen in QL mice normalizes L-type Ca\textsuperscript{2+} channel activity,\textsuperscript{29} which, taken with the present study, is likely through restoration of T-tubule architecture. Based on the mechanism we uncovered for T-tubule remodeling in QL hearts, we would presume that, with tamoxifen withdrawal and normalization of G\textsubscript{xq} signaling, a decrease in calpain activity precedes restoration of JP-2 expression, T-tubule ultrastructure and synchronous SR Ca\textsuperscript{2+} release.

A number of studies have now shown that the disrupted T-tubule structure can be restored by increasing the expression of SERCA2, exercise, cardiac resynchronization therapy or mechanical unloading,\textsuperscript{5,21,54–56} suggesting that the T-tubule network is a dynamic, regulated structure. In the present study, we conclusively demonstrate that the restoration of T-tubule ultrastructure is possible once the insulting stimulus causing the disruption is terminated. Our results suggest that the molecular mechanism responsible for this remodeling cycle is the onset and termination of JP-2 proteolysis.

Heart failure is a complex multifaceted syndrome as heart disease of different etiologies approaches end stage. In addition to T-tubule (ultra)structural remodeling, many other mechanisms, including \(\beta\)-adrenergic receptor unresponsiveness, oxidative stress, protein kinase C activation, SR calcium handling abnormalities, metabolic inhibition, mitochondria dysfunction, and so on, are also critically involved in the pathogenesis of heart failure. It is possible that constitutive activation of G\textsubscript{xq} also contributes to some or all of these pathogenic pathways. For example, constitutive G\textsubscript{xq} activation may also alter RyR2 organization, although, as far as we know, there is no evidence in the literature that G\textsubscript{xq} signaling regulates RyR2 organization. T-tubule remodeling may cause redistribution and loss of \(\beta\)-adrenergic receptors in the T-tubules in failing cardiomyocytes.\textsuperscript{54,57} Thus, our findings complement previous findings and provide new insights into the mechanistic role of myocyte ultrastructural alterations in heart failure development and progression.

Each of the key steps of the signaling cascade “G\textsubscript{xq} activation \(\rightarrow\) elevation of calpain activity \(\rightarrow\) JP-2 dysregulation \(\rightarrow\) T-tubule remodeling \(\rightarrow\) heart failure” is known to be a common alteration existing in many forms of heart disease. For example, many studies have established that G\textsubscript{xq} signaling plays a critical role in the development of cardiac hypertrophy and heart failure.\textsuperscript{26,27} Calpain activity has also been found to be increased in a variety of pathological conditions.\textsuperscript{58–63} Our study provides evidence of a sequential mechanistic linkage among these events and therefore provides new insights into our understanding of heart failure pathogenesis in general heart disease. The fact that disrupted T-tubule networks can undergo repair, plus the ability of the calpain inhibitor to block T-tubule disruption, holds promise for the development of interventions to modulate JP-2 levels as a treatment for heart failure. Drugs and nonpharmacological approaches designed to block the degradation or enhance the level of JP-2 may improve the contractile dysfunction in heart failure.

In summary, our data reveal that T-tubule structural remodeling is a reversible process that mirrors the status of cardiac function. Calpain-mediated JP-2 proteolysis represents the molecular mechanism by which JP-2 is degraded, leading to T-tubule disruption, Ca\textsuperscript{2+} handling dysfunction, and progression of heart failure.

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Disclosures

None.

References


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