Irregular Rhythm Adversely Influences Calcium Handling in Ventricular Myocardium: Implications for the Interaction Between Heart Failure and Atrial Fibrillation

Ling et al: Effects of Heart Rhythm on Ca\textsuperscript{2+} Handling in HF

Liang-han Ling, MBBS\textsuperscript{1}; Ouda Khammy, BSc\textsuperscript{1}; Melissa Byrne, PhD\textsuperscript{1}; Fatemah Amirahmadi, PhD\textsuperscript{1}; Anna Foster, BSc\textsuperscript{2}; Gefeng Li, PhD\textsuperscript{1}; Linda Zhang, PhD\textsuperscript{2}; Cris dos Remedios, PhD\textsuperscript{1}; Chen Chen, MBBS PhD\textsuperscript{2}; David M. Kaye, MBBS PhD\textsuperscript{1,4}

\textsuperscript{1}Heart Failure Research Group, Baker IDI Heart and Diabetes Institute, Melbourne, Australia; \textsuperscript{2}School of Biomedical Sciences, University of Queensland, Brisbane, Australia; \textsuperscript{3}Muscle Research Group, University of Sydney, Australia; and \textsuperscript{4}Dept Medicine, Monash University, Melbourne, Australia

Correspondence to
Professor David M Kaye
Baker IDI Heart and Diabetes Research Institute
PO Box 6492
St. Kilda Road Central, Melbourne, Victoria, Australia 8008
Ph. 613-85321111
Fax. 613-85321100
Email: david.kaye@bakeridi.edu.au

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Abstract

Background—Despite adequate rate control, the combination of atrial fibrillation (AF) with heart failure (HF) has been shown in a number of studies to hasten HF progression. In this context we aimed to test the hypothesis that an irregular ventricular rhythm causes an alteration in ventricular cardiomyocyte excitation-contraction coupling which contributes to the progression of HF.

Methods and Results—We investigated the effects of electrical field stimulation (average frequency 2Hz) in an irregular vs regular drive train pattern on the expression of calcium handling genes and proteins in rat ventricular myocytes. The effect of rhythm on intracellular calcium transients was examined using Fura 2AM fluorescence spectroscopy. In conjunction, calcium handling protein expression was examined in left ventricular samples obtained from end-stage HF patients in patients with either persistent AF or sinus rhythm (SR). Compared to regularly paced ventricular cardiomyocytes, in cells paced irregularly for 24hrs there was a significant reduction in the expression of the sarcoplasmic reticulum Ca\(^{2+}\)ATPase (SERCA) together with reduced serine-16 phosphorylation of PLB. These findings were accompanied by a 59% reduction (p<0.01) in the peak Ca\(^{2+}\) transient in irregularly paced myocytes compared to those with regular pacing. Consistent with these observations, we observed a 54% (p<0.05) decrease SERCA protein expression and an 85% (p<0.01) reduction in the extent of phosphorylation of phospholamban (PLB) in the left ventricular myocardium of HF patients in AF compared to those in SR.

Conclusions—Together these data demonstrate that ventricular rhythmicity contributes significantly to EC coupling by altering the expression and activity of key calcium-handling proteins. These data suggest that control of rhythm may be of benefit in patients with HF.

Key Words: atrial fibrillation; heart failure; excitation-contraction coupling; calcium handling proteins; cardiomyocytes
Atrial fibrillation (AF) and heart failure (HF) are both common cardiovascular disorders which are each associated with significant morbidity, mortality, and health expenditure. These two conditions are often encountered together in clinical practice, and it has been suggested that their combination is accompanied by particularly adverse outcomes, although this remains controversial. In particular, in several large HF cohorts it has been shown that the presence of AF confers increased risk of heart failure related mortality, although other studies have not observed this interaction.

Although many mechanisms have been proposed to account for the adverse influence of AF on HF, these remain somewhat speculative in many cases with little characterisation at the molecular level. Firstly, haemodynamic factors including loss of atrial transport, valvular regurgitation, and persistently irregular ventricular cycles have been shown to contribute to reduced cardiac output or increased pulmonary capillary wedge pressure independently of heart rate in a range of in vivo models. Secondly, chronic elevation of heart rate associated with AF may induce tachycardia-mediated cardiomyopathy. Here, the degree of induced left ventricular (LV) dysfunction is related to the rate and duration of tachycardia and recovery of LV systolic function is expected following restoration of normal sinus rhythm (SR). Subgroup analyses of both retrospective and prospective clinical cohorts indicate that the adverse influence of AF on HF might also be explained by the presence of an irregular rhythm per se, based on observations that the reversion to SR in patients with LV dysfunction leads to improved LV function even in subjects with adequate rate control. These data suggest that issues beyond rate control and haemodynamic effects may play a larger role in the interaction between AF and HF than generally assumed.
In the present study, we aimed to test the hypothesis that prolonged irregular activation of ventricular cardiomyocytes and the ventricular myocardium leads to a hastening of the molecular remodeling in ventricular myocardium that occurs in HF. In particular, it is well known that major changes in excitation-contraction coupling occur in HF with abnormal calcium cycling and alterations in expression of calcium regulatory proteins including the sarco(endo)plasmic reticulum ATPase 2a pump (SERCA) and phospholamban (PLB) \(^{23,24}\). We therefore examined the effects of irregular rhythm of the expression of calcium handling genes and proteins and their functional consequences.

**Methods**

All studies were performed with the approval of the relevant Institutional Review Committees, which included the Human Research Ethics Committee at St Vincent’s Hospital, NSW, Australia; Alfred Medical Research and Education Precinct Animal Ethics Committee; and the University Animal Ethics Committee of the University of Queensland. Investigations confirmed with the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes (2004), and the principles outlined in the Declaration of Helsinki.

**Cardiomyocyte Cell Culture and Electrical Field Stimulation**

Neonatal rat ventricular cardiomyocytes (NVCMs) were isolated from day 1 to 2 Sprague-Dawley rat pups by collagenase digestion as previously described \(^{25}\). Cardiomyocytes from each isolation were plated at a density of 1.4 \(\times\) 10\(^6\) cells/well on 3 separate four-well rectangular pacing plates (Nunclon, Nalge Nunc International). Following 24 h of serum deprivation, cells were paced for 24 h using a purpose-designed electric field stimulation system (C-Pace EP, IonOptix, Boston, MA, USA). To simulate ventricular activity during normal SR, regular electrical stimulation was delivered at 2Hz. AF was simulated by
irregular electrical stimulation which was generated by a pre-programmed irregular drive sequence derived from an inbuilt repeating sequence of 100 intervals (Figure 1). Using this sequence, the pacing interval was programmed to vary by ±60% around an average drive stimulus interval of 0.5 seconds. As such, cardiomyocytes paced regularly or irregularly are electrically stimulated the same total number of times over the 24 hr period. In all pacing experiments, cardiomyocytes were paced at 20 V using a pulse width of 4 msec and electrical capture was confirmed under light microscopy at the start and end of each pacing period. Following 24 hr pacing, cells either underwent protein extraction for further analysis, or were loaded with fura-2AM for measurement of calcium transients. Pacing did not affect cell viability as assessed by Trypan blue (MP Biomedicals, CA USA) uptake, nor pH of the culture media (data not shown).

**Human Ventricular Myocardial Samples**

LV myocardial samples were obtained from 12 patients with LV ejection fraction (EF) <35% undergoing heart transplantation for end-stage HF. We specifically selected tissue samples from stored tissue bank material from 6 patients in sinus rhythm and 6 patients that were in chronic AF. The cause of HF was non-ischemic cardiomyopathy in 6/6 and 5/6 patients respectively. Control LV myocardial samples were also obtained from 3 unused donor hearts. The tissue samples were immediately frozen in liquid nitrogen and stored at -80°C. Tissue collection was performed with the approval of the Institutional Ethics Review Committees.

**Cell Lysate and Homogenate Preparation**

Human LV homogenates were prepared using a handheld homogenizer (TissueRuptor, Qiagen, MD, USA) in ice-cold phospholysis buffer containing (mM): 10 Tris-HCL (pH 7.5), 50 NaCl, 100 NaF, 10 Na$_3$P$_2$O$_7$, 1 Na$_3$VO$_4$, 2 DTT, 1% Triton X-100, and protease inhibitor
cocktail (Roche, NSW, Australia). Phospholysis buffer was also applied to NVCMs. Samples were centrifuged at 2,500 g for 10 minutes and again at 10,000 g for 10 minutes to remove debris. Total protein concentration of the supernatant was determined using a protein assay kit (Bio-Rad, CA, USA), with remaining supernatant flash-frozen for storage at –80°C.

**Determination of Protein Expression by Western Immunoblotting**

Ten to 50 μg of protein contained in whole-cell lysates were combined with Laemmli’s sample buffer (Bio-Rad, CA, USA), fractionated using sodium dodecyl sulfate polyacrylamide gel electrophoresis, and transferred onto polyvinylidene fluoride membranes. As appropriate blots were probed with primary antibodies recognizing SERCA, total and phosphoserine-16 forms of phospholamban (t-PLB and ps16-PLB), RYR and NCX. The blots were finally incubated in horseradish peroxidase-conjugated goat anti-rabbit or goat anti-mouse secondary IgG antibody, and target protein bands were detected by using a Western Blot Chemiluminescence Reagent Plus detection system (ECL Plus). Housekeeping band evaluation was performed using β-tubulin for human samples and GAPDH for rat samples. Quantification of band density was performed using Quantity One software (Bio-Rad). Primary antibodies were from Abcam for p-PLB, Cell Signalling for RYR, Santa Cruz for GAPDH while all other primary and secondary antibodies were acquired from Affinity Bioreagents (CO, USA).

**Determination of mRNA Expression using Real-time Polymerase Chain Reaction (PCR)**

Total RNA was extracted from human LV homogenates and NVCMs using Trizol reagent (Invitrogen), purified (Ambion DNA-free Kit, Applied Biosystems, CA, USA), and reverse-transcribed (Taqman Reverse Transcription Reagents, Applied Biosystems). Real-time PCR was performed using SYBR green dye and using a 7300 Real-time PCR System (Applied
Biosystems). The following primers were used: SERCA – forward 5’-GAAGGCCTGGATTGTGCAA-3’, reverse 5’-GGTTTTCGACAAGCTGTGA-3’; NCX – forward 5’-GCCCTCCTGTTTGCATTACGT-3’, reverse 5’-TGGAGACAATGAAACACGCC-3’; RYR2 – forward 5’-GCCCTCCTGTTTCGATTACGT-3’, reverse 5’-GGTTTTCGGACAAGCTGTTGA-3’; NCX

was used as the housekeeping gene.

**Fluorescence Measurement of NVCM Calcium Transients**

Following 24 h of SR pacing, AF pacing, or no pacing in controls, intracellular calcium was determined in NVCMs using microspectrofluorimetry under regular 1 Hz pacing conditions using an Ionoptix calcium imaging system. In brief, cells were loaded with 5.0 μM fura-2-AM then the media replaced with physiologic buffer containing (mM): 139 NaCl, 3 KCl, 17 NaHCO3, 12 Glucose, 3 CaCl2, and 1 MgCl2, pH 7.4. Changes in fluorescent emission at 510 nm recorded with a CCD camera, following alternate excitation at 340 nm and 380 nm, were collected and analysed using image analysis software. [Ca2+]i was measured as the ratio of fura-2 fluorescence emission at 340 nm and 380 nm (F340/F380).

**Statistical Analyses**

Results are expressed as mean ± standard error of the mean (SEM). For tissue culture expression studies, data were derived from 6 independent myocyte preparations. For between group comparisons, the Student’s t-test was used for normally distributed data and the Mann-Whitney rank sum test was used for non-normal data. For comparisons of more than 2 groups, either one- or two-way analysis of variance (ANOVA) was used, followed by host-hoc Tukey’s multiple comparison tests (for fluorescence imaging analyses) or Bonferroni tests.
(for molecular biological analyses) respectively to compare paired means. In all analyses, p<0.05 was taken as significant. Statistical analysis was performed using SPSS version 19.

**Results**

**Influence of Electromechanical Rhythmicity on Ca^{2+} Handling Protein Expression**

We first evaluated the effect of irregular ventricular rhythm on the mRNA and protein expression of SERCA, and its key regulator phospholamban, given their critical role in determining of the intracellular Ca^{2+} concentration. These studies were conducted in both human left ventricular tissue and paced rat cardiomyocytes. As shown in Figure 2A and C, the expression of SERCA protein expression was significantly lower ventricular myocardium obtained from HF patients in AF as compared to healthy control myocardium (56% reduction, p<0.05) and ventricular myocardium obtained from HF patients in sinus rhythm (54% reduction, p<0.01). In keeping with this finding, the abundance of SERCA mRNA was significantly lower in failing ventricular myocardium from patients in AF as compared to control myocardium (78% reduction, p<0.005) and ventricular myocardium from HF patients in sinus rhythm (66% reduction, p<0.005). Similar to observations in human heart, we found a significant reduction in the expression of both SERCA protein (Figure 2B and D) and mRNA (19±8%, p<0.05) in irregularly paced rat ventricular cardiomyocytes, suggesting that rhythm per se does influence SERCA expression beyond any effect of heart failure.

Using the same approach we demonstrated a significant effect of rhythm on the abundance of phosphorylated phospholamban in relation to total phospholamban expression. As shown in Figure 3A and C, there was a significant hypophosphorylation of phospholamban in ventricular samples obtained from HF patients. More specifically, compared with control samples, the ratio of phosphoserine 16 abundance to total phospholamban expression was
reduced by 60% in SR samples (p<0.05) and by 94% in AF samples (p<0.02), and the extent of phospholamban phosphorylation was significantly lower in ventricular samples from HF patients in AF as compared to those in sinus rhythm (p<0.01). In support of these observation irregularly paced cardiomyocytes exhibited a 57 ± 4% (p<0.05) reduction in the level of phospholamban phosphorylation (Figure 3B and D), compared to regularly paced myocytes. Whilst the level of phospholamban phosphorylation was influenced by rhythm, there was no evidence of an effect on the abundance of total phospholamban protein (Figure 3) or mRNA in either human myocardium or in paced myocytes.

To complement the observations on the expression of SERCA and phospholamban, we also examined the influence of rhythm on the mRNA and protein expression of the ryanodine receptor (RYR) and the sodium-calcium exchanger (NCX) in both human tissue and paced rat cardiomyocytes. In failing human left ventricular myocardium from patients in sinus rhythm, there was a 38% decrease in RYR mRNA expression (p<0.05) compared to that in healthy control tissue. In comparison to tissue from the sinus rhythm group, the RYR mRNA abundance was decreased significantly further in heart failure patients in AF (50%, p<0.05). At the protein level (Figure 4), decreased RYR expression was evident in heart failure samples compared to controls 1.8±0.3 vs 0.5±0.2 au, p<0.05) but there did not appear to be a between group difference with regard to rhythm. By contrast, in paced myocytes the abundance of RYR mRNA was increased significantly in irregularly paced cardiomyocytes as compared to regular pacing (59±24%, p<0.05), however no change in the abundance of RYR protein was evident. In both failing left ventricular myocardium and in paced cardiomyocytes we did not detect any effect of rhythm on the expression of NCX (Figure 4).
**Effect of Rhythm on [Ca\(^{2+}\)]\(_i\) in Ventricular Myocytes**

To determine the whether the alterations in the expression of SERCA and phosphorylated phospholamban associated with altered rhythm resulted in an alteration in intracellular Ca\(^{2+}\) handling we performed calcium imaging rat cardiomyocytes after 24 h of irregular or regular electrical stimulation. As shown in Figures 5 and 6, the Ca\(^{2+}\) transient amplitude was significantly reduced in irregularly paced NVCMs compared with regularly paced or unpaced NVCMs (59% and 82% respectively, p<0.0001). By detailed analysis of the Ca\(^{2+}\) transient we also observed that the time to 10%, 50%, and 90% of peak calcium from baseline was prolonged in AF versus SR paced NVCMs (Figure 5B), while the rate of calcium decay reflected by time to 10%, 50%, and 90% return to baseline did not appear to change significantly across groups (Figure 5C).

**Discussion**

The present study sought to establish whether the clinically observed adverse association between AF and HF could be explained by a deleterious effect of *irregular* electromechanical activity on *ventricular* cardiomyocytes. To best of our knowledge we showed for the first time that irregular stimulation of ventricular cardiomyocytes, to simulate the ventricular activity in atrial fibrillation, is associated with a significant downregulation of SERCA and in the ratio of phosphorylated to total phospholamban. These changes were associated with significant alterations in the regulation of intracellular calcium levels.

As outlined above we sought to specifically distinguish the impact of rhythmicity on cardiomyocyte function, separate to the effects of rate in poorly controlled AF. Previous work by Lenaerts and colleagues evaluated mechanical function, Ca\(^{2+}\) handling and cell structure in atrial myocytes obtained from sheep with AF induced by rapid atrial pacing \(^{26}\). Consistent
with our study, they showed that AF caused a significant reduction in the amplitude of the Ca$^{2+}$ transient, which was accompanied by reduced contractility. In contrast to our study however, this was proposed to be the result of a altered coupling between the L-type Ca$^{2+}$ channel and the ryanodine receptor. Of note, the present study differed in several respects to that of Lenaerts including the effect of differences in rate per se between myocytes obtained from sheep in SR to those in AF and the use of atrial myocytes which express ion channels in different proportions to that of ventricular cardiomyocytes. In the present study we did not measure cardiomyocyte contraction because of the difficulties associated with measuring true cell shortening in neonatal cardiomyocytes.

Previous studies of SERCA abundance in failing human LV myocardium have generally shown reduced mRNA and protein expression compared to non-failing hearts. A clear relationship between SERCA protein abundance or activity and contractile function has been demonstrated in some, although not all studies. HF has also been associated with reduced serine-16 phosphorylation of PLB. Together, these changes contribute to reduced SERCA activity and SER calcium loading, diminished calcium-induced calcium release, and consequently depressed contractile response. Reduced SERCA activity also results in diastolic impairment due to delayed elimination of cytosolic calcium following contraction although in the current study we did not detect a prolongation of the time to restoration of basal intracellular calcium levels. In the present study we could not attribute this to enhanced expression of NCX as suggested by others.

In our study, we did not observe a significant difference in SERCA protein expression between failing myocardium from patients in SR and non-failing LV myocardium. Of note, this is consistent with a number of negative studies, with larger positive studies...
recognizing a wide range of SERCA expression to exist in LV myocardium from both non-failing and failing hearts of up to 2-fold and 4-fold respectively. Our findings suggest consideration of the underlying heart rhythm may also be of relevance in the interpretation of some of these previous studies. Although the role of SERCA has been extensively studied in HF, the cellular mechanisms responsible for the changes in expression are largely unknown. Some indirect evidence suggests that calcium may influence the expression of SERCA via an incompletely understood nuclear factor of activated T-cells (NFAT) mediated mechanism.

In addition to the level of SERCA protein expression, the corresponding level of PLB expression and its relative level of phosphorylation is also a critical determinant of SERCA activity and thus intracellular calcium homeostasis. We found that in both the failing human heart and in our cell culture model, the presence of an irregular rhythm was accompanied by a significant reduction in the ratio of phosphorylated to total PLB, whilst the overall level of PLB was unchanged. The notion that the relative hypo-phosphorylation of PLB could contribute to a reduction in ventricular function is supported by studies in which a pseudo-phosphorylated form of PLB was introduced into isolated cardiomyocytes or the intact heart, demonstrating an improvement in ventricular function in the setting of experimental HF. Phosphorylation of PLB is well-understood to be regulated via the influence of protein kinase A, typically under the activation of beta adrenergic receptors. Conversely, the de-phosphorylation of PLB is mediated via protein phosphatase 1 (PP1), which has also been implicated in the pathogenesis in HF although its role in AF is unknown. Furthermore in the setting of heart failure it has been previously shown that reduced levels of inhibitor-1 protein together with its degree of phosphorylation may account for the increased activity of PP1 and thus diminished PLB phosphorylation. As a functional correlate of our
observations in paced myocytes, we found that there was a marked reduction in the peak intracellular calcium concentration in comparison to regularly paced ventricular myocytes. This would be consistent with the depletion of SER calcium in the setting of reduced SERCA activity, and would be expected to translate into reduced contractility.

In the present study, we found a reduction in the expression of RYR protein and mRNA in failing myocardium, an effect that was further enhanced in the presence of atrial fibrillation. To date, studies of RYR expression have not yielded uniformly consistent findings in human heart failure. In addition to the expression of RYR per se, extensive several studies also highlight the role of post-translation modifications of RYR including hyperphosphorylation, nitrosylation and oxidation, together with the role of regulatory protein-protein interactions in determining the open probability of the RYR channel (as reviewed recently \(^1\)). Whilst point mutations involving RYR and possibly phosphorylation of RYR may increase \(\text{Ca}^{2+}\) through RYR channels contributing to the generation of ventricular arrhythmias it is not certain whether this process also reduced cardiac contractility \(^44, 45\). In the present study we did not investigate the effect of rhythm on RYR phosphorylation, and the sample size was too small to discern a specific effect of concomitant pharmacologic therapies.

Although our studies in cardiomyocytes were performed in rat neonatal cardiomyocytes, these cells are frequently used for studies of gene and protein regulation. Our study was designed to specifically compare the differential effect of irregular versus regular electromechanical activity on gene and protein expression, together with calcium handling although it is known that some differences in excitation-contraction coupling exist between neonatal and adult cardiomyocytes \(^46\). In the present study we did not investigate the effects of rhythmicity on ion channel activity or cell-cell communication. Notwithstanding the
potential limitations of neonatal myocytes our cellular studies were consistent with those found in studies on human myocardium.

As a corollary of our study it might be predicted that the conversion of patients with HF in AF to SR could be accompanied by evidence of improved ventricular function. Indeed, van Gelder and colleagues previously showed that cardioversion from AF caused a progressive rise in left ventricular ejection fraction over a 1 month period. Moreover the increase in LV function did not track changes in atrial mechanical function, leading to the conclusion that AF induced a cardiomyopathic process. Subsequently, several clinical studies have been conducted to investigate the effect of rhythm versus rate control on survival and ventricular function in patients with AF. In the AFFIRM study there were no differences in mortality between the two management strategies. This study was limited by the presence of relatively few HF patients and low success in SR maintenance. Of note, a further analysis of the AFFIRM study did show that the presence of SR was associated with better survival. In the RACE study, Hagens and colleagues compared the effects of rate versus rhythm control strategies in HF patients with AF. Similar to the AFFIRM study, this study failed to demonstrate a difference between the two treatment groups, however the study was also limited by the fact that only 36% of patients in the rhythm-control group were in sinus rhythm at follow-up. Interestingly in that study, a multivariate analysis suggested that the presence of SR was associated with improved left ventricular function. More recently a large scale multicentre trial compared rate versus rhythm control in patients with more advanced HF. This study demonstrated that both treatment strategies were equal with regard to survival and heart failure hospitalization. Whilst this study does not necessarily support the hypothesis that AF leads to an acceleration of HF progress, it is important to note that these patients did not have sustained atrial fibrillation at recruitment and during follow-
up there was heterogeneity of rhythm across both treatment groups. This issue also confounds the recent RECORDAF study which showed that while AF patients receiving a rhythm management strategy had fewer hospitalizations the interpretation of the study is complicated by the limit success of the rate and rhythm strategies and the higher baseline incidence of heart failure in the rate control group.

Given the major limitations of pharmacologic strategies for rhythm control, other investigators have used more definitive electrophysiologic approaches. Ferreira and colleagues showed that AV node ablation in conjunction with biventricular pacing resulted improved survival and reduced hospitalization compared to patients in AF with a biventricular pacemaker. This study is supported by a previous meta-analysis which showed that AV node ablation improved ventricular function, which together are consistent with the present study.

Limitations

Our study has several limitations. Our study made use of human tissues obtained from transplant recipients and unused donor hearts. Detailed information regarding the use and doses of inotropic therapy, anti-arrhythmics, beta-blockers and digoxin was not available in all patients. Accordingly it was not possible to match in detail AF and non-AF patients. In the present study we studied the compared the effect of regular versus irregular electromechanical activity on Ca²⁺ handling and Ca²⁺ handling protein expression in neonatal cardiomyocytes to understand the potential effects of AF in HF. These studies were of a short term nature, and they may not necessarily reflect the influence of persistent or permanent AF. We did not specifically study the effects on cardiomyocyte contractility and did not evaluate to effects on other intracellular signalling pathways which may also affect contractility.
Taken together, our study demonstrates in ventricular cardiomyocytes and intact myocardium that irregular cycles of excitation and contraction induce an altered profile of gene and protein expression, that are associated with functional changes at a cellular and tissue level. These data were derived from series of consistent studies performed using complimentary approaches that include isolated cardiomyocyte and explanted human heart samples. These observations may provide an explanation for the deleterious interaction between AF and HF. Our study provides support for continued investigation into the effect of strategies that effectively restore regular ventricular rhythm in HF patients with AF.

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**Disclosures**

None.

**References**


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Figure Legends

**Figure 1.** Irregular pacing protocol comprising 100 randomly assigned stimulus intervals, with an average interval of 500 msec (2Hz).

**Figure 2.** Representative immunoblots showing SERCA expression in A. human left ventricular myocardium from unused donor heart (C), heart failure-sinus rhythm (SR) and heart failure-atrial fibrillation (AF) patients; B. regularly paced vs irregularly paced cardiomyocytes. Quantitative analysis of SERCA expression in C. human myocardial samples (*p<0.05 control vs AF; **p<0.01 SR vs AF) and D. Isolated paced cardiomyocytes (*p<0.05 regular vs irregular).

**Figure 3.** Representative immunoblots showing phospholamban and phosphorylated-phospholamban expression in A. human left ventricular myocardium from unused donor heart (C), heart failure-sinus rhythm (SR) and heart failure-atrial fibrillation (AF) patients; B. regularly paced vs irregularly paced cardiomyocytes. Quantitative analysis of phosphorylated:total phospholamban expression in C. human myocardial samples (*p<0.05 control vs AF; **p<0.01 SR vs AF) and D. Isolated paced cardiomyocytes. (*p<0.05 regular vs irregular).

**Figure 4.** Representative immunoblots showing ryanodine receptor (RYR) and sodium calcium exchanger (NCX) expression respectively in A, C. human left ventricular myocardium from unused donor heart (C), heart failure-sinus rhythm (SR) and heart failure-atrial fibrillation (AF) patients; B, D. regularly paced vs irregularly paced cardiomyocytes.
**Figure 5.** Representative calcium transients presented as F340/380 ratio from cardiomyocytes following 24 h of regular (above) or irregular (below) pacing (2Hz). Calcium transients were acquired at a stimulus frequency of 1Hz.

**Figure 6.** Calcium transient group data from cardiomyocytes following 24 hours of no pacing (Cont), regular paced or irregular pacing. Measurements were made under regular pacing at 1 Hz. (A) Peak calcium transient amplitude. (B) Rate of rise to peak calcium transient reflected by time to reach 10%, 50%, and 90% of peak (T\textsubscript{p10}, T\textsubscript{p50}, and T\textsubscript{p90}). (C) [Ca\textsuperscript{2+}]\textsubscript{i} decay rate represented by time to 10%, 50%, and 90% return to baseline (T\textsubscript{b10}, T\textsubscript{b50}, and T\textsubscript{b90}). Data obtained from at least 16 cells per group, from 3 independent myocyte isolations *p<0.05; **p<0.001; ***p<0.0001, ns= not significant.
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