Electromechanical dyssynchrony can markedly worsen heart failure (HF) morbidity and mortality, independent of traditional risk factors. Depending on the metric used, current estimates of the prevalence of dyssynchrony vary from 25–30% in patients with HF (based on QRS widening) up to 60%, based on tissue Doppler or MRI measures of dysynchronous contraction of the left ventricle (LV). Cardiac resynchronization therapy (CRT) or biventricular pacing has emerged as a promising option to treat patients with HF and dyssynchronous contraction. The past few decades have seen the rise of pharmacotherapy, primarily through agents that antagonize the effect of excessive concentrations of circulating neurohormones, yet, HF-related morbidity and mortality remain high. Biventricular stimulation has been demonstrated to improve contractile performance in patients with mechanical dyssynchrony acutely and chronically while also prolonging long-term survival—something not yet achieved by drug therapy. Although the clinical and mechanical effectiveness of CRT are well described, 30% of patients do not benefit from CRT and clinical criteria to identify CRT nonresponders remain elusive. Currently, the most widely used predictor of reverse remodeling is the presence of marked mechanical dyssynchrony before CRT, as indexed by the width of the QRS. Mechanical dyssynchrony seems important, yet imaging-based measures have not predicted response well and even improvement in dyssynchrony after initiation of CRT only weakly predicts chronic response. Limited understanding of the molecular mechanisms underlying reverse cardiac remodeling induced by CRT has hampered the selection of potential responders. In this review, we focus on the electrophysiological aspects and molecular networks underlying the benefits of CRT. We will review how CRT homogenizes regional differences in stress kinase signaling and electric remodeling and then review its global effect on myocyte function and its broader impact on the cardiac ventricular transcriptome. A comprehensive understanding of the molecular features of dysynchronous contraction in the failing heart (DHF) and its reversibility by biventricular pacing promises to identify sets of biological markers for the selection of patients who will benefit most from CRT and, in a more general sense, to advance our knowledge of HF-associated pathophysiological processes.

Beyond the Mechano-Energetics

Until recently, the prevailing view of CRT efficacy is that it reduces mechanical inefficiency from disorganized contraction, allowing more blood to be ejected at a lower energy cost. Multisite ventricular pacing had been proposed for ventricular arrhythmia termination and ultimately for improvement in hemodynamic performance in patients with HF. CRT was developed in the mid-1990s after investigators found that biventricular (or LV only) preexcitation could restore mechanical synchrony and improve acute LV mechanics, energetic efficiency, and regional metabolism. Subsequent large-scale clinical trials demonstrated that CRT can acutely and chronically enhance cardiac work and systolic performance in selected patients. Using a canine model of dyssynchronous ventricular contraction, our group has corroborated the mechanical benefits of CRT. Dogs treated with biventricular rapid pacing after an initial period of dysynchronous HF of 3 weeks had a slight but significant improvement in ejection fraction and stroke volume, whereas both ejection fraction and stroke volume continued to decline in dogs with continued HF with dyssynchronous contraction (DHF) (Figure 1A). In this model, resynchronization of LV contraction was confirmed by MRI circumferential uniformity ratio estimate (CURE) index or standard tissue Doppler parameters (Figure 1B). The observed improvement of myocardial function in both animal models and HF patients raised the question of whether wall motion is all there is to LV preexcitation, or whether effective CRT might also reverse cellular remodeling. In fact, another mechanical circulatory support mechanism, LV assist devices are known to induce myocardial changes at the cellular and structural level such that a small number of patients may recover sufficient cardiac function that permits device removal. Hints at changes in cellular signaling pathways by CRT first came from human studies of responders versus “nonresponders,” where myocardial gene expression changes of calcium handling proteins, molecular and electrophysiological mechanisms underlying the benefits of CRT.

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β-receptors, and natriuretic peptides were reversed preferentially in responders. Patients with effective CRT display chronic enhancement of circulating apelin, a secreted hormone that can block adverse remodeling and has positive inotropic effects. Circulating biomarkers of extracellular matrix remodeling also accompanies successful CRT, including decreases in tenascin-C, and matrix metalloproteinase 9.

Chronic CRT also has anti-inflammatory effects and reduces monocyte chemoattractant protein-1, interleukin-8, and interleukin-6 levels. Although these studies do not identify the underlying mechanisms by which CRT exerts its beneficial effect, they may suggest biomarkers for therapies that both enhance systolic function and survival in HF patients.

**Regional Molecular Changes in HF and CRT**

**Stress Response Kinases**

Initial molecular insights into DHF were provided in a report by our group examining the regional effects of DHF on molecular signaling. This study revealed the selective downregulation of Ca²⁺ handling proteins and connexin 43 and upregulation of mitogen-activated protein kinase in the lateral wall only, referred to as molecular polarization. This regional molecular change was not observed in synchronous HF. In a more recent study by Chakir et al., the lateral wall of DHF ventricles exhibited an increase in p38 MAPK and Ca²⁺-calmodulin kinase II (CaMKII) activation and increased tumor necrosis factor (TNF)-α expression, which were both reversed by CRT (Figure 2). These localized differences in stress kinase activation were consistent with disparities in regional work load in DHF and its equalization by CRT (Figure 1). The changes in stress response kinases are potentially important, given the impact of these proteins on muscle function, survival, and fibrosis. P38 MAPK stimulates fibrosis and apoptosis and is associated with contractile failure. CaMKII is an important mediator of β-adrenergic-related toxicity leading to apoptosis, cardiac hypertrophy, and the generation of cardiac arrhythmias. TNF-α stimulates fibrosis and apoptosis, and overexpression induces dilated cardiomyopathy. Expression TNF-α can be...
Electrophysiological Changes in DHF and CRT

In addition to molecular polarization, DHF is characterized by regional heterogeneities in cellular and tissue electrophysiological properties. The hallmark signature of cells and tissues isolated from failing hearts, independent of the etiology, is action potential (AP) prolongation.\(^4^4\)–\(^5^0\) AP prolongation in DHF is most prominent in cells isolated from the late-activated lateral LV wall and is an index of the exaggeration of the physiological heterogeneity of electric properties in the failing heart.\(^5^1\) CRT significantly shortens the AP in lateral myocytes and thus reduces LV regional heterogeneity in action potential duration (APD) (Figure 3). Regional alterations in ionic currents underlie the AP remodeling; however, the molecular mechanisms of regional ionic current remodeling in DHF and CRT are controversial. A prominent increase of TNF-\(\alpha\) and CaMKII in the lateral wall might play a role in regional AP remodeling. TNF-\(\alpha\) increases oxidative stress in HF activates CaMKII and triggers ventricular arrhythmias. CaMKII modulates Ca\(^{2+}\) currents, sarcoplasmic reticulum (SR) function,\(^5^2\)–\(^5^5\) and increases persistent Na\(^+\) current,\(^5^6\)–\(^5^7\) resulting in prolongation of APD.\(^5^8\) It is possible and indeed likely that other regional alterations in Ca\(^{2+}\) handling or increased persistent Na\(^+\) current contribute to regional differences in the APD and AP profile in DHF, and the regionally specific effects of biventricular pacing on this phenotype.

Effects of DHF and CRT on the Regional LV Transcriptome

In previous studies, we demonstrated that CRT can reverse the regional heterogeneities of electric remodeling and stress response kinases. However, this may be just the tip of the iceberg because most analyses were focused on individual proteins and most likely missed a broader impact of dysynchrony and CRT on regional molecular expression patterns. To test this hypothesis, we used a global gene expression profiling approach in the aforementioned canine model of dysynchronous HF and CRT that allowed us to examine mRNA expression in anterior and lateral LV myocardium. As a result of this unbiased and global assessment of transcriptional activity, we identified more than 6 times as many genes to be differentially expressed between nonfailing and DHF hearts in anterior compared with lateral LV myocardium of the same hearts (2173 versus 346 transcripts, respectively; false discovery rate <5\%).\(^5^9\) We found prominent downregulation of metabolic pathways (oxidative phosphorylation, fatty acid, amino acid, and glucose metabolism), whereas various cell-signaling pathways were upregulated (MAPK, JAK-STAT, TGF-\(\beta\)) in the anterior LV wall of the dysynchronous failing heart. The greater downregulation of metabolic transcripts in anterior compared with lateral LV regions is also in good agreement with human studies: using gated PET with 18F-fluorodeoxyglucose and 99mTc-sestamibi single-photon emission-computed tomography to noninvasively measure myocardial glucose metabolism and myocardial perfusion, respectively, Nowak et al\(^6^0\) found that glucose metabolism is reduced more than perfusion in the anteroseptal compared with LV lateral wall in patients with DCM and left bundle-branch block.

Importantly, the disparity in the number of regulated transcripts between the early- and late-activated LV regions gave rise to an increased regional heterogeneity of gene expression within the dysynchronously contracting LV myocardium. These dys synchrony-induced regional gene expression changes were reversed by CRT to levels comparable to nonfailing hearts (Figure 4). Experimentally, this has been shown to couple with rebalancing of glucose metabolism\(^6^1\) and myocardial blood flow\(^6^2\) (rising in the anterior and declining in lateral walls), and such findings are consistent with CRT-associated increases in transcripts levels encoding oxidative phosphorylation and various metabolic pathways in anterior samples. Our results indicate that by recoordinating contraction, regional heterogeneity of gene expression can be essentially returned to normal, even in a failing heart, on a genome-wide level.

Global Effects of CRT on Myocyte Function

In addition to reversing regional molecular polarization, CRT globally corrects electrophysiological abnormalities and improves \(\beta\)-adrenergic responsiveness and mitochondrial energetic...
efficiency. All these changes may play an important role in the ability of CRT to enhance the systolic work performance of the failing heart acutely and chronically while also improving long-term survival.

**CRT Reverses K⁺ Channel Remodeling and Reduces Afterdepolarizations**

Downregulation of K⁺ currents is the most consistent ionic current change in animal models 47,49,50,61 and human HF. K⁺ current downregulation may promote ventricular tachycardia/ventricular fibrillation50 either by direct prolongation of AP44 in the voltage range at which I_Ca,L reactivation occurs, predisposing to the development of early afterdepolarizations, 62 or by heterogeneously reducing repolarization reserve and promoting functional reentry.63 CRT dramatically reduces the frequency of early afterdepolarizations in cells isolated from both the anterior and lateral LV (Figure 5A and 5B).

We recently reported on these modifications in more detail, revealing that DHF significantly reduced the inward rectifier (I_K1), delayed rectifier (I_K), and transient outward potassium currents (I_TO) in both anterior and lateral myocytes. 51 CRT restored DHF-induced K⁺ current reductions throughout the ventricle, with the exception of I_TO (Figure 5C through 5E). In fact, K⁺ channels are the most diverse class of ion channels. The detailed changes in K⁺ channels vary with the model of HF or with species.64 I_TO is unique among regulated K⁺ currents in HF because it is downregulated uniformly in HF45–47,50,65 yet not reversed by CRT (Figure 5C).51 In parallel, Kv4.3 and KChIP2 mRNA and protein expression are down-regulated in DHF without restoration by CRT (Figure 5F).51

I_K1 (Kir 2 family of genes) maintains the resting membrane potential and contributes to terminal repolarization. Reduced inward I_K1 density in HF 46,49,66,67 may contribute to prolongation of APD and enhanced susceptibility to spontaneous depolarizations including delayed afterdepolarizations (DADs).67,68 CRT, even in the setting of continued HF, partially restores I_K1 density (Figure 5D),51 decreases membrane resistance, and, in the setting of improved Ca²⁺ handling in CRT (see below), may reduce the frequency of arrhythmogenic DADs. Kir2.1 mRNA and protein levels are partially restored by CRT in the canine model (Figure 5F).51

I_K plays a prominent role in the late phase of repolarization69; therefore changes in either the slow (I_Ks) or fast (I_Kr) activating components of this current could contribute significantly to AP prolongation in HF. CRT partially restores DHF-induced downregulation of I_K density in both anterior and lateral LV myocytes without a significant change in mRNA or protein levels of KvLQT1 or mink subunits for I_Ks, whereas mRNA level of ERG, a subunit of I_Kr, was restored by CRT in both the anterior or lateral LV wall (Figure 5E and 5F).51

**Ca²⁺ Handling in DHF and CRT**

HF is associated with major changes in Ca²⁺ handling, which underlies the observed reduction in force of contraction of the
failing heart. Consistent with this HF phenotype, myocytes isolated from DHF hearts showed calcium transients with a markedly reduced peak amplitude and slowed kinetics in both the anterior and lateral wall (Figure 6A). CRT dramatically restored both the amplitude and kinetics of the Ca\textsuperscript{2+} transient. This result is striking, recalling that our CRT model involves 6 weeks of tachypacing, and CRT and DHF hearts have a similar degree of LV dilation and elevation of end-diastolic pressure.

On a beat-by-beat basis, the Ca\textsuperscript{2+} transient is elicited by the influx of a small amount of Ca\textsuperscript{2+} through L-type Ca\textsuperscript{2+} currents (I_{Ca,L}) and the subsequent large-scale Ca\textsuperscript{2+} release from the SR through the ryanodine receptor (RyR2). During diastole, cytosolic Ca\textsuperscript{2+} is taken up into the SR by the phospholamban (PLN)-regulated SR Ca\textsuperscript{2+}-ATPase (SERCA2A). In DHF, we found that the reduction of I_{Ca,L} and Ca\textsuperscript{2+} transients is more pronounced in the lateral wall versus the anterior wall. Importantly, CRT restored the DHF-induced reduction of peak I_{Ca,L} density, thus eliminating the anterior-lateral I_{Ca,L} density gradient (Figure 6B). However, no significant differences in Ca\textsubscript{v}1.2 (Ca\textsubscript{v}\alpha1C) mRNA and protein or Ca\textsubscript{v}\beta1 subunit mRNA expression were found among control, DHF, and CRT hearts (Figure 6C). Yet, Ca\textsubscript{v}\beta2 mRNA was decreased significantly in DHF but not in CRT myocytes when compared with non-failing myocardium.

We further tested for the molecular basis of changes in the Ca\textsuperscript{2+} transient. We found that mRNA and protein levels of SERCA2A, PLN, and RyR2 were downregulated and Na\textsuperscript{+}/Ca\textsuperscript{2+} exchanger (NCX1) upregulated without a change in CRT (Figure 6C). There were also no regional differences in mRNA and protein expression in any of these mediators of Ca\textsuperscript{2+} handling in DHF and CRT. These results suggest that the differences of Ca\textsuperscript{2+} handling in DHF and its restoration by CRT are posttranslational.

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**Figure 5.** Cardiac resynchronization therapy (CRT) reverses K\textsuperscript{+} channel remodeling and reduces early afterdepolarization (EADs). A, Representative superimposed action potentials (APs) recorded in myocytes isolated from the lateral wall of dysynchronous heart failure (DHF) hearts with EADs. B, Bar plot of frequency of EADs (%EADs indicates fraction of APs with EADs). C through E, DHF significantly reduces the inward rectifier I_{K1}, the delayed rectifier (I_{K}) and transient outward K\textsuperscript{+} currents (I_{to}) in both anterior and lateral cells. CRT partially restores the DHF-induced reduction of I_{K1} and I_{K}, but not I_{to} in both anterior and lateral cells. F, Changes in steady-state K\textsuperscript{+} channel mRNA subunit and protein expression. ANT or A indicates anterior; LTR or L, lateral. Modified from Aiba et al.\textsuperscript{51}
Rest and β-Adrenergic–Stimulated Myocyte Contractility

The first hint of a positive impact of CRT on cardiac β-signaling was provided by clinical studies demonstrating reduced muscle sympathetic nerve activity in patients with severe HF and dysynchrony and CRT-mediated enhanced neural norepinephrine reuptake and retention. To more directly study myocyte β-adrenergic signaling, our group measured sarcomere shortening after administration of isoproterenol. Consistent with many models of HF, DHF myocytes displayed highly blunted contractility at rest and during stimulation with isoproterenol compared with myocytes from nonfailing hearts. Both basal and isoproterenol-stimulated cell shortening were markedly improved by CRT throughout the ventricles, and their recovery was well correlated with an increase in the amplitude and hastening of the kinetics of the Ca2+ transients (Figure 7A).

We examined the underlying mechanisms for enhanced β-adrenergic responsiveness by CRT. Both β1- and β2-receptor gene expression and receptor number were depressed by DHF, and CRT enhanced β1- but not β2-receptor number, as in humans. Functional analysis of adenyl cyclase activity revealed that it was also depressed by DHF, and CRT augmented cAMP production. Among the most striking changes, however, was inhibitory G-protein (G_i)-coupled signaling. As shown in Figure 7B, myocytes from DHF hearts showed marked potentiation of the isoproterenol response if the myocytes were first incubated with pertussis toxin, which inhibits G_i. In contrast, CRT myocytes displayed enhanced responses at baseline and showed no effect with pertussis toxin, as if G_i already was inhibited by CRT. Consistent with human HF, G_in was upregulated in both DHF and CRT animals and can therefore by itself not account for the enhanced β-adrenergic responsiveness with CRT. However, we found selective upregulation of proteins called regulators of G-protein signaling (RGS) (Figure 7C). RGS proteins negatively regulate G-coupled signaling by acting as selective GTPase accelerators, removing GTP from the activated α-subunit and allowing the trimeric G-protein complex to reform suppressing G-protein–coupled signaling. RGS3, a protein known to suppress Gi, was selectively upregulated in human CRT responders as well as canine models of resynchronization. Moreover, CRT appeared to improve contraction through RGS-mediated enhancement in coupling of β2-adrenergic receptors to stimulatory G-proteins (G_s). Activation of the β2-G_s axis may represent a general strategy to improve functional reserve in patients with HF and dyssynchronous contraction, perhaps even those who do not respond to CRT.

Cell Survival Signaling

As reported both in humans and in our canine model, DHF hearts display an increase in apoptosis. In the canine pacing tachycardia model, this was supported by TUNEL staining, caspase-3 activity, and nuclear poly ADP-ribose polymerase cleavage. Importantly, apoptosis was suppressed by CRT. One of the most striking changes was a marked decline in Akt phosphorylation/activity with DHF that was also reversed by CRT (Figure 8). Akt is generally considered a prosurvival kinase, and Akt phosphorylation of the proapoptotic protein BAD results in the interaction of BAD with the chaperone Bcl-XL that retards apoptosis.

BAD remains unknown. It is unlikely that improved LV function, which is modest in this model with CRT, accounts for the changes in Akt signaling. However, activation of secreted factors coupled to the abnormal mechanical loading may prove an important pathway, and this is currently being explored.
CRT and Mitochondria

Given the central role of mitochondria in apoptosis pathways, the improved survival signaling prompted us to test the hypothesis that mitochondrial function was favorably altered by CRT. Agnetti et al. compared changes in mitochondrial protein expression and posttranslational modification between DHF and CRT animals in lateral LV myocardium, demonstrating salutary effects on mitochondrial respiration and efficiency of oxidative phosphorylation with CRT. Using optimized 2D electrophoresis of the mitochondrial subproteome, ≈1200 protein spots were resolved, revealing 31 quantitative protein changes between DHF and CRT. Most changes were in proteins of the respiratory chain, including all of the complexes of oxidative phosphorylation (except complex IV; Figure 8), consistent with CRT modulating ATP production. CRT also increased the metabolic pathways supplying the substrates (pyruvate carboxylase and pyruvate dehydrogenase, E1 and E2 subunits) and key enzymes (aldehyde dehydrogenase, α-keto acid dehydrogenase E2, and ferredoxin reductase) fuelling the Krebs cycle. Importantly, mitochondrial oxidative efficiency (ADP/O2) was depressed by DHF and enhanced by CRT. CRT also reduced oxidative stress, potentially by enhanced mitochondrial reactive oxygen species–scavenging proteins. These mitochondrial changes have not been reported with other HF therapies, and may represent a selective response to CRT.

Conclusions

We and others have found profound basic cellular and molecular changes in DHF, many of which are not observed in HF with synchronous ventricular contraction. Remarkably, CRT specifically targets and reverses many of these changes. Some of the observed cellular and molecular alterations appear global in nature, though some cascades exhibit regional specificity, for example, activation of stress kinases in the late activating lateral wall and transcriptional changes in the anterior wall. The improvement in cell survival and increase in potassium currents, myocyte contractility, and β-adrenergic receptor responsiveness occur throughout the ventricle. These results suggest that CRT can influence the failing heart in a way that enhances both regional mechanical work and global pump function and may be the basis for improved long-term survival with CRT. The relative contributions of global versus regional cellular and molecular signaling in DHF and CRT remain incompletely understood. We hypothesize that the beneficial effects of CRT on global myocardial function result from restoration of the normal sequence of excitation and contraction involving local,
region-specific myocardial changes in neurohumoral activation and mechanical forces. Ongoing studies are attempting to further investigate this interesting question.

The characteristic molecular and electrophysiological alterations of DHF also promise to identify a molecular signature through which CRT ameliorates the HF phenotype. As noted, HF and depressed ejection fraction do not necessarily predict the response to specific pharmacological therapies, and variations in the underlying genetics as well as molecular and cellular biology are increasingly thought to be key determining factors. We do not yet know whether underlying cellular and/or molecular signaling responses to dyssynchrony vary among individuals with DHF, but we speculate that a lack of depressed Akt activation, IK signaling, or upregulated Gi coupling in a given DHF patient might diminish the effectiveness of CRT. The level of molecular heterogeneity may prove to be a useful marker that dyssynchrony has adversely affected the ventricle function beyond HF-specific molecular changes.

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None.

References


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