Advances in Heart Failure

Molecular and Cellular Basis of Viable Dysfunctional Myocardium

Marina Bayeva, PhD; Konrad Teodor Sawicki, BS; Javed Butler, MD; Mihai Gheorghiade, MD; Hossein Ardehali, MD, PhD

Heart Failure and Functional Recovery

Heart failure is a leading cause of healthcare expenditures, hospitalization, and mortality in developed countries, and its burden is growing globally. With the aging of the population and increasing prevalence of chronic diseases, including hypertension, diabetes mellitus, and obesity, the current heart failure epidemic is guaranteed to significantly worsen in the near future. Thus, new disease-modifying treatments for heart failure are needed urgently and represent an area of intense investigation.

Multiple studies in humans and animals have shown that the functionality of myocardial tissue of a failing heart can be restored. First, in ischemic heart failure because of severe coronary artery stenosis, revascularization therapy is known to improve heart function in a proportion of patients. Second, the mechanical unloading of the heart by left ventricular assist device (LVAD) is associated with improvements in cardiac function. In a recent report of 80 patients with heart failure who underwent implantation of a continuous-flow LVAD, the ejection fraction increased by >50% in about one third of the patients, with corresponding improvements in LV end-systolic and end-diastolic volumes and decreases in LV mass at 6 months after LVAD unloading. In addition, normalization of echocardiographic parameters has obviated completely the need for continuing LVAD support or cardiac transplantation in several patients. Importantly, the positive effects of mechanical unloading were noted in patients with both ischemic and nonischemic heart failure, suggesting that dysfunctional but potentially salvageable segments of myocardium exist in the failing heart regardless of pathogenesis. Third, in patients with broken heart syndrome (also known as Takotsubo cardiomyopathy), characterized by a rapid and severe loss of cardiac contractility secondary to emotional stress, myocardial function normalized spontaneously, again arguing for the reversibility of heart failure. In summary, although maladaptive changes observed in failing hearts were initially considered to be terminal, the accumulating body of evidence argues strongly for the reversibility of cardiac dysfunction because of multiple and distinct pathogeneses, raising the exciting possibility of curing the failing heart.

Myocardial Adaptations to Ischemia: A Continuum

Initially, it was thought that myocardial ischemia resulted in either irreversible myocardial necrosis (ie, myocardial infarction) or complete and rapid recovery of myocyte function (ie, typical angina). However, it is now clear that ischemia produces a continuum of myocardial adaptive responses (Figure 1). Several animal models have shown that resting contractile dysfunction is dependent on the physiological significance of the coronary stenosis, which can progress from a state associated with normal resting flow to a state with regional reductions in resting flow. The degree of stenosis severity determines many of the intrinsic molecular adaptations of the myocardium, and this continuum of adaptations may be partly responsible for the variable time course and extent of reversibility of cardiac function after revascularization.

For example, myocardial stunning is a brief, fully reversible depression of cardiac function, usually of <24 to 48 hours in duration. Myocardial stunning mostly occurs after a single brief episode of ischemia and is associated with normal resting myocardial blood flow. Heyndrickx et al demonstrated myocardial stunning by subjecting the hearts of conscious dogs to no-flow ischemia for 5 or 15 minutes and showing depression in mechanical function for 3 to >24 hours after reperfusion, respectively, but with subsequent complete recovery. Myocardial stunning can occur in several clinical settings, such as exercise in the presence of coronary stenosis and variant angina.

On the contrary, myocardial hibernation develops in response to repetitive ischemia or worsening chronic coronary stenosis. It is characterized by a series of adaptations in the setting of reduced regional resting flow to preserve myocardial viability at the expense of ventricular function. Myocardial hibernation may also result from repetitive stunning because of repeated ischemia, and it is now widely thought that myocardial stunning and hibernation are part of a continuum disease spectrum. Although myocardial stunning and hibernation are both reversible, myocardial stunning is usually fully reversible within 1 to 2 days, whereas hibernating myocardium may require several days to months to recover.
who suggested that prolonged subacute or chronic ischemia attributable to limited coronary blood flow causes the heart to reduce its energy/oxygen utilization by suppressing myocardial metabolism and contractile force. Thus, the smart heart establishes a new equilibrium between cardiac energy supply and demand to maintain its viability in the setting of hypoperfusion. However, the reduction in coronary flow in the ischemic heart central to this hypothesis remains controversial, with many studies reporting no change in baseline perfusion of the dysfunctional myocardium.\(^{21-23}\) Subsequently, another hypothesis argued that in the setting of limited coronary flow reserve, a transient elevation in myocardial metabolic demand because of exercise or adrenergic stimulation causes short but frequent episodes of ischemia and myocardial stunning. Although each individual stunning episode is fully reversible within 24 hours, multiple bouts of ischemia will lead to sustained depression of contractile function.\(^{24}\) This repetitive stunning hypothesis has been validated in large animal models of sublethal ischemia–reperfusion, which recapitulate the pathology of the human heart, although the suppression of myocardial function may be deliberate and adaptive in accordance with the smart heart hypothesis. Unfortunately, the mechanism by which the myocardium loses its functionality in nonischemic heart failure has not been well characterized and remains an important, but understudied, area of research.

### Structural Changes in VD Myocardium

In the setting of decreased myocardial blood flow, the heart undergoes structural remodeling, involving changes in the morphology and protein content of the myocardium, to maintain contractility. As a result of this remodeling, the VD myocardium may take months to fully recover its function once blood flow is restored.\(^{25}\) A large number of structural changes have been described in VD cardiomyocytes in both humans and animal models of ischemic cardiomyopathy. Biopsies of dysfunctional myocardium obtained during coronary bypass surgery in humans revealed replacement of sarcomeres in the perinuclear area by deposits of glycogen and mitochondria.\(^{26-28}\) There was also a profound reduction in, and disorganization of, the sarcoplasmic reticulum and abnormalities in the size and shape of mitochondria.\(^{26,28}\) Based on these morphological changes, VD ischemic cardiomyocytes were proposed to dedifferentiate to resemble fetal cells, a hypothesis that was supported by identification of embryonic/fetal gene isoforms in adult VD myocardium, including \(\alpha\)-smooth muscle actin, titin, desmin, and cardiacin.\(^{30-32}\)

Two mechanisms were proposed to mediate the return of the VD myocyte to an embryonic/fetal morphology: myocardial ischemia and mechanical stretch. The first mechanism seems to be less likely, as similar changes in cardiomyocyte morphology and signs of dedifferentiation were detected in other models of cardiac dysfunction, including chronic atrial fibrillation,\(^{33}\) infarct border zone,\(^{34}\) and in explanted hearts from patients with heart failure.\(^{35}\) Moreover, many changes that are prominent in the viable region of the dysfunctional myocardium were also detected in the remote, nonischemic zones, arguing for a heart-wide mechanism.\(^{27,36,37}\)

The stretch hypothesis was supported by studies in vitro and in a pig animal model of chronic coronary stenosis.
Coculturing of adult rabbit ventricular myocytes with fibroblasts was shown previously to induce a pattern of dedifferentiation similar to that of VD myocardium and thus was used as a model to elucidate the molecular mechanisms for this phenomenon. The authors reported redistribution of adhesion molecules, such as β-1 integrin, N-cadherin, desmoplakin, and vinculin, from the intercalated disc area at the distal end of cardiomyocytes to the lateral membranes of these cells, thus increasing the tensile force experienced by cardiac myocytes. The myocytes were cultured under normoxic conditions, ruling out the role of ischemia in dedifferentiation. Although the model of cardiomyocyte–fibroblast coculture may not fully recapitulate all of the ultrastructural changes that occur during chronic dysfunction of the myocardium, its findings are nevertheless supported by studies in pigs, in which cardiomyocyte dedifferentiation was noted after 2 weeks of coronary stenosis. Importantly, in addition to expression of fetal α-smooth muscle actin, there was a significant loss of desmoplakin and desmin from the intercalated disks on immunofluorescent staining, with no change in the total content of these proteins present in cells. Interestingly, the changes in adhesion molecules were not restricted to the dysfunctional ischemic myocardium but were also observed in the well-perfused remote zones of the heart, similar to previous reports of myofibrillar loss in both dysfunctional and normal myocardium.

Whether mechanical stretch plays a role in the development of nonischemic heart failure is still not known. However, a gene array analysis of recovered and nonrecovered myocardium after LVAD removal or cardiac transplantation revealed striking differences in the expression of β-integrins, the transmembrane sensors of stretch signals. Thus, the mechanical stretch may also play a role in the suppression of cardiac function in nonischemic hearts, although the detailed mechanism remains to be elucidated.

**Molecular Mechanisms of VD Myocardium**

Although significant research has been devoted to understanding the structural and functional changes that occur in VD myocardium, little progress was made in elucidating the molecular mechanisms governing suppression and recovery of myocardial function attributable to both ischemic and nonischemic cardiomyopathy.

The studies of ischemic VD myocardium in human patients were conducted by comparing the molecular profiles of dysfunctional ischemic myocardium and nonischemic remote zones. In addition, some investigators compared ischemic VD myocardium with control nonmyopathic donor hearts. The majority of animal studies on ischemic VD myocardium were conducted in swine and canine models, in which myocardial dysfunction was induced either by various protocols of repetitive stenosis and reperfusion or by surgically narrowing coronary arteries for chronic reduction in cardiac perfusion. These models display suppression of myocardial contractile function and molecular changes in cardiomyocytes reminiscent of the VD ischemic myocardium in human patients.

For evaluation of VD myocardium in patients with nonischemic heart failure, myocardial samples were taken from patients during the implantation of LVAD and after removal of the device on recovery of cardiac function. In addition, a series of studies examined the myocardium of patients who received LVAD as a bridge to transplantation, although many of these studies failed to record the extent of functional recovery of the failing heart and correlate the molecular changes to the restoration of cardiac viability.

The molecular changes that occur in VD myocardium because of ischemic pathogenesis include alterations in contractile proteins, depression of energy metabolism and mitochondrial function, disruption of calcium signaling and sensitivity, and induction of a distinct subset of cardioprotective genes (Figure 2). Similar pathways are affected in nonischemic failing hearts, and mechanical unloading was shown to normalize their function. Unfortunately, it remains unknown which of these pathways are primarily responsible for the depression of myocardial contractility in heart failure, and which are altered nonspecifically, secondary to neurohormonal axis activation, increased workload of the heart, or other processes.

**Myofibrillar Proteins**

Myocardial cells contain several myofibrils, long chains of individual sarcomeres composed of alternating thick and thin myofilaments that coordinate cardiac contraction and relaxation. The reduction in contractility of ischemic VD myocardium may be purely related to the structural changes associated with long-term coronary perfusion-consumption mismatch or may represent an adaptive mechanism, which minimizes energetically expensive myofibrillar cycling. Several changes in structural and signaling proteins in myofilaments of VD myocardium have been described, all consistent with suppressed contractility. In a model of limited coronary flow for 24 hours in a pig heart, a reduction in myofibrillar volume density was observed but returned to normal after 7 days of reperfusion, supporting the reversibility of the VD myocardial phenotype. A recent unbiased proteomic analysis of dysfunctional and healthy remote heart tissue from a pig model with chronic coronary artery stenosis identified several contractile proteins differentially expressed in VD myocardium. Among those were thin filament proteins, including troponin, tropomyosin, myosin light chains, and myosin heavy chain β. In addition, Elsässer et al found significant loss of myofilaments in 38 patients with identified VD myocardium, characterized by reductions in the protein and mRNA content of actin, α-actin, myosin, desmin, and titin. Consistent with depressed contractility, a reduction in phosphorylation of myosin regulatory light chain 2 and cardiac troponin I was observed in a novel mouse model of myocardial dysfunction in which chronic ischemia was induced by vascular endothelial growth factor (VEGF) sequestration. Because phosphorylation of myosin regulatory light chain 2 is critical for cardiac muscle contraction, dephosphorylation of this protein may be a potential mechanism that significantly limits contractility in the VD heart. These findings suggest that structural disassembly and altered regulation of myofilament proteins contribute to cardiac dysfunction in VD myocardium.

In nonischemic human failing hearts, profound changes in myofibrillar proteins also took place in the setting of LVAD support. In a study comparing hearts that recovered their function with LVAD to those that failed to show
improvement, sarcomeric proteins, β-actin, α-tropomyosin, α1-filamin A, and α1-actinin, were increased in the recovered group. However, troponin T, α2-actinin, and syntrophin levels were lower in the recovered hearts compared with the nonrecovered ones. At the protein level, there was a significant increase in myosin heavy chain, troponins C and T, sarcomeric actin, and other cytoskeletal proteins in hearts whose function was restored with mechanical unloading, suggestive of their suppression in VD myocytes. Finally, LV AD support was associated with changes in post-translational modifications of contractile proteins, including reduced protein kinase A-dependent phosphorylation of troponin I. In summary, VD myocardium shows a wide range of changes in myofibrillar proteins, and restoration of cardiac function is associated with reorganization of the contractile apparatus. However, it is difficult to compare the changes that occur in myofibrils of ischemic and nonischemic failing cardiomyocytes, and it remains to be determined whether interventions targeting myofibrillar dynamics will be effective in treating myocardial dysfunction.

Calcium-Handling Proteins

Maintenance of calcium handling is essential for cardiomyocyte contraction. On depolarization of the cardiomyocyte cell membrane by an action potential, L-type calcium channels are activated and the resulting calcium influx leads to calcium-induced calcium release from the sarcoplasmic reticulum, raising the cytosolic calcium concentration. This cytosolic calcium binds to and activates cross-bridge attachments in myofilaments, leading to muscle contraction. Disruption of proteins mediating calcium flux is associated with reduced contractile force. A study of regional myocardial short-term ischemia in pigs showed a decrease in overall myocardial calcium responsiveness of VD segments, suggestive of an excitation–contraction coupling defect. Follow-up investigations revealed significant reductions in mRNA and protein levels of sarcoplasmic reticulum Ca2+-ATPase (SERCA), responsible for calcium uptake into the sarcoplasmic reticulum during the relaxation phase. SERCA2a activity was also reduced in heart homogenates from patients with documented VD myocardium, compared with control nonmyopathic hearts. This finding may be explained by dephosphorylation of SERCA inhibitor phospholamban, which would block SERCA2 action through physical interaction with this transporter. Expression and activity of calcium-handling proteins were also altered in nonischemic cardiomyopathy and reversed with LVAD-mediated unloading. Thus, LVAD support increased SERCA2a protein and mRNA levels in the failing hearts regardless of heart failure pathogenesis.

The functional characterization of calcium homeostasis in VD myocardium is scarce, but nevertheless supports the notion of repressed calcium flux (Figure 3). Both Ca2+ influx and free intracellular Ca2+ concentration were reduced in ischemic VD myocardium, consistent with an excitation–contraction coupling defect. In nonischemic hearts supported with LVAD, there was a similar depletion of intracellular Ca2+ stores, which was improved by mechanical unloading. Defects in other parameters of calcium transients were also reversed in the recovered nonischemic hearts, including normalization of the force–frequency relationship, faster time-to-peak and decay of the Ca2+ transient, and shortening of the action potential. Consistently, myocyte force generation was significantly improved after mechanical unloading. In summary, although the exact changes in the expression and activity of calcium-handling proteins remain to be resolved,
it seems that calcium homeostasis is severely disrupted in VD myocardium and may be partially responsible for the reduction in contractile force, whereas the recovery of myocardial function correlates with normalization of calcium handling in cardiomyocytes.

**Energy Metabolism**

The majority of studies on energy metabolic remodeling in VD myocardium are limited to the ischemic cardiomyopathy. VD ischemic myocardium displays a profound remodeling of energy metabolism, which is proposed to be an adaptive response to coronary hypoperfusion. The major changes that occur in VD myocardium include suppression of oxygen consumption and mitochondrial function with a concomitant upregulation of glucose uptake and utilization (Figure 3).

Several studies reported a reduction in mitochondrial oxygen consumption and reduced respiratory control index in the VD myocardium in a pig model with chronic coronary stenosis. Similarly, a study of human patient biopsies revealed reduced oxygen consumption and oxidative phosphorylation capacity in chronically ischemic myocardium. These changes were paralleled by a coordinated downregulation of many mitochondrial enzymes and subunits of mitochondrial electron transport chain complexes, and ATP synthase, consistent with VD myocardium in a swine model with chronic coronary artery constriction demonstrated increased expression of mitogen-activated protein kinase p38, which correlated with increased membrane localization of the glucose transporter 4, increased membrane localization of the glucose transporter 4, and increased glucose transporter 4 expression in VD cardiomyocytes. This may be explained by upregulation of glucose transporter 1, which may be mediated by the hypoxia inducible factor-1 signaling pathway. In addition, a study in pigs with chronic coronary artery constriction demonstrated increased expression of mitogen-activated protein kinase p38, which correlated with increased membrane localization of the glucose transporter 4, although the causal relationship between the 2 events and the mechanism by which mitogen-activated protein kinase is induced in VD myocardium were not established.

The switch of preferred substrate from fatty acids to glucose in VD myocardium provides the rationale for using radionuclide myocardial perfusion imaging with glucose analogs, such as 18F-FDG, to differentiate VD myocardium from nonviable myocardium. This is an established, noninvasive method of simultaneously imaging myocardial perfusion and metabolism through the use of positron-emitting isotopes. Regional reperfusion is assessed using an isotope that remains in the vascular space, such as nitrogen-13 ammonia or rubidium-82, to demonstrate blood flow distribution. Enhanced FDG uptake in regions of decreased blood flow (PET mismatch) represents VD myocardium, whereas a reduction in both FDG uptake and blood flow (PET match)
represents primarily necrotic myocardium. Therefore, PET imaging can differentiate among normal, VD, and necrotic myocardium. Compared with dobutamine echocardiography, \(^{18}\)F-FDG PET has improved sensitivity and negative predictive value in detecting VD myocardium.\(^7\) The detection of VD myocardium by \(^{18}\)F-FDG PET is important in the management of patients with heart failure, as regions designated as VD myocardium by PET have an 80% to 85% chance of functional improvement after coronary revascularization, whereas regions designated as necrotic myocardium have only a 20% chance of improvement after revascularization.\(^7\)–\(^9\)

Several radiolabeled fatty acid (FA) compounds are also under clinical investigation for use in myocardial viability imaging. FAs used in myocardial viability imaging are commonly labeled with the single-photon emitter, \(^{123}\)I, or more rarely with the position-emitting radionuclide, \(^{11}\)C, and require structural modification to prolong myocardial clearance of the tracer. For example, \(^{123}\)I-iodophenylpentadecanoic acid (IPPA) is a radiolabeled straight chain FA with a phenyl group substituted at the \(\omega\)-carbon, which stabilizes the iodine on the molecule to inhibit \(\beta\)-oxidation at its terminal end.\(^8\) Under nonischemic conditions, IPPA is rapidly metabolized, whereas under ischemic conditions, myocardial fatty acid metabolism is suppressed, resulting in longer myocardial retention of IPPA and a redistribution pattern on serial single-photon emission computer tomography (SPECT) imaging.\(^8\)\(^1\)\(^1\) In a prospective, multicenter trial to evaluate the use of \(^{123}\)I-IPPA SPECT for the detection of VD myocardium, 119 patients underwent \(^{123}\)I-IPPA SPECT imaging and blood-pool radionuclide angiography before coronary artery bypass graft (CABG).\(^8\) Radionuclide angiography was also repeated 6 to 8 weeks after CABG. Although the number of IPPA-viable myocardial segments was the most significant predictor of improved ejection fraction, the overall sensitivity and specificity of IPPA were low (48% and 79%, respectively). Methyl-branched analogs of IPPA, such as \(^{123}\)I-(\(p\)-iodophenyl)-3-(R,S)-methylpentadecanoic acid, demonstrate superior protection from \(\beta\)-oxidation.\(^8\)\(^4\)\(^5\) This modification slows down the rapid dynamics of FA metabolism to allow for more accurate SPECT imaging.\(^8\)\(^4\)\(^1\)\(^1\) \(^{123}\)I-(\(p\)-iodophenyl)-3-(R,S)-methylpentadecanoic acid has been well studied in patients with ischemic heart disease and is currently the only radiolabeled FA available for clinical use in some parts of the world, particularly Japan.

In addition to radiolabeled FA compounds, \(^{11}\)C-acetate is a radiolabeled 2-carbon compound that is rapidly metabolized to \(^{11}\)C-acetyl-CoA in the mitochondria, where it enters the tricarboxylic acid cycle and undergoes oxidative phosphorylation to yield \(^{14}\)CO\(_2\) and H\(_2\)O.\(^6\) The myocardial uptake rate of \(^{11}\)C-acetate is proportional to myocardial blood flow, whereas the rate of clearance of \(^{11}\)C-acetate from the myocyte reflects the rate of myocardial oxygen consumption (MV \(\text{O}_2\)).\(^5\) Therefore, the uptake and turnover of \(^{11}\)C-acetate as assessed by PET can potentially be used as a single-tracer technique to yield quantitative data on both flow and metabolism, respectively. Despite significant progress in our understanding of energy metabolism in VD myocardium, several important questions remain unanswered. First, the debate exists about the adaptive versus maladaptive role for metabolic remodeling in the ischemic VD hearts. Recently, Stride et al\(^6\) described mitochondria isolated from VD human hearts as dysfunctional, citing diminished mitochondrial oxidative capacity, increased reactive oxygen species production, and reduced antioxidant defenses. Others have characterized the suppression of mitochondrial function as an adaptive mechanism, based on preservation of multiple energetic indices despite the overall reduction in metabolic rate.\(^7\)\(^6\)\(^6\)\(^7\)\(^8\) These include preserved phosphocreatine-to-ATP ratio,\(^7\)\(^6\)\(^6\)\(^8\) maintenance of the ATP-to-ADP ratio,\(^8\) and a slower rate of ATP depletion,\(^7\) suggestive of energetic efficiency of the VD heart. Finally, despite reduced mitochondrial function and lower \(\text{O}_2\) consumption at rest, VD myocardium was able to increase its metabolism and use diverse energy substrates in response to an increased workload without the development of ischemia.\(^6\)\(^4\)\(^5\)\(^7\)\(^8\) Thus, the cellular energetics remains robust in VD myocardium despite the suppression of mitochondrial oxidative phosphorylation, which may be an adaptive response that prevents a supply-demand imbalance in the setting of limited coronary flow reserve.

The question of how suppression of energy metabolism is achieved during the transition toward myocardial dysfunction in heart failure still remains unanswered, with no molecule or pathway emerging as a possible master regulator of energy metabolism in VD myocytes. Hu et al\(^8\) showed that in addition to VD segments, energy homeostasis is also suppressed in remote zones with no evidence of ischemia or reduction in contractility, suggesting the involvement of a circulating humoral factor. However, Stride et al\(^8\) detected significant differences in mitochondrial oxidative phosphorylation between functional and dysfunctional regions of the same human heart. Thus, the question remains unresolved and additional mechanistic studies are needed.

**Cytoprotective and Stress–Response Pathways**

Fully differentiated cardiomyocytes have reduced capacity for regeneration, and death of myocytes is linked to various forms of cardiac pathology. Thus, the ability of cardiomyocytes to survive cytotoxic insults is indispensable for maintenance of the heart’s health. Most of the early studies examining survival pathways in ischemic VD cardiomyocytes focused on the role of heat shock protein 70 (HSP70) in the heart,\(^5\)\(^6\)\(^9\)\(^1\) whereas newer studies used unbiased genomic and proteomic approaches to identify additional stress–response and cytoprotective genes in VD myocardium.\(^9\) These genes included a powerful suppressor of caspases, inhibitor of apoptosis, stress–response genes HSP27 and HSP70, as well as a novel growth-promoting H11 kinase (H11K). The findings were further validated in human heart failure with PET-confirmed VD cardiac segments. Both, mRNA and protein levels of inhibitor of apoptosis, HSP70 and H11K were significantly upregulated in VD human myocardium, compared with the remote normal tissue.\(^72\)

Although the role of inhibitor of apoptosis and HSP27/HSP70 in preservation of cell viability was previously established,\(^9\)\(^4\)\(^6\)–\(^9\) the function of H11K in VD myocardium remains unknown. H11K was linked to various forms of cancer,\(^7\)\(^9\)\(^8\) and cardiac-specific overexpression of H11K in the mouse resulted in significant hypertrophy, with increased cardiac cell diameter and volume.\(^9\) It has been suggested that H11K may promote myocyte viability through an increase in glucose uptake. Consistently, a 3-fold increase in glucose transporter
1 expression and accumulation of glycogen were found in the hearts of H11K-transgenic mice, mimicking the changes observed in VD myocardium. Yet, the causative role for the H11K pathway in induction and maintenance of VD myocardium has not been established definitively.

Other Mechanisms
Differences in several additional pathways and molecules have been noted in VD myocardium, but little progress has been made in elucidating their role in a failing heart. For example, the levels of the proinflammatory cytokine tumor necrosis factor-α were elevated by >13-fold in human ischemic VD myocardium. Moreover, high tumor necrosis factor-α levels were found in nonischemic failing hearts before LV AD implantation, and a reduction in tumor necrosis factor-α was observed after mechanical unloading. Importantly, accumulation of tumor necrosis factor-α in the heart was shown previously to suppress contractility and damage cardiac function.

In addition, the levels of inducible nitric oxide synthase (also known as NOS2), which generates an important modulator of heart function, NO, were significantly upregulated in 2 independent studies of human patients with ischemic VD myocardium. NOS2 expression has also colocalized with that of cyclooxygenase-2, the enzyme that generates superoxide anion. Because the reaction of superoxide with NO produces a strong oxidant peroxynitrite, physical proximity of the 2 enzymes may significantly boost oxidative stress and damage cardiomyocyte structural components. Consistently, elevated levels of nitrotyrosine, a marker of peroxynitrite formation, were found in VD sections of the heart and colocalized with cyclooxygenase-2 and NOS2 expression. Yet, the role of peroxynitrite in the pathology of VD myocardium remains to be determined.

The regional adaptations of VD myocardium also include myocyte loss via an apoptotic mechanism. In swine with chronic left anterior descending occlusion, Lim et al demonstrated that VD myocardium was associated with myocyte apoptosis, leading to compensatory regional cellular hypertrophy independent of replacement fibrosis. This may represent a common mechanism through which repetitive ischemia and elevations in LV filling pressure lead to a similar molecular phenotype in VD myocardium independent of changes in coronary perfusion. Although clinical studies on the importance of myocyte apoptosis in VD myocardium have yielded mixed conclusions, these differences may be explained by the low overall frequency of apoptosis and time-dependent variations in the magnitude of apoptosis during the development of VD myocardium.

Autophagy was also upregulated in VD myocardium after the third cycle of repetitive ischemia–reperfusion bouts in pigs. Importantly, induction of autophagy correlated temporally with a decrease in apoptosis, and thus was suggested to play a protective role in the VD heart. In a mouse model of chronic ischemia through VEGF sequestration, autophagy was also identified as a key prosurvival mechanism.

Finally, the neurohormonal response was altered in VD myocardium, as partial sympathetic denervation of VD myocytes and changes in the expression of α- and β-adrenergic receptors were reported in both ischemic and nonischemic heart failure.
occlusion or immediately before reperfusion.\textsuperscript{123,124} Ehring et al\textsuperscript{125} studied the role of bradykinin in the beneficial effects of ramiprilat in open-chest dogs subjected to occlusion of the left circumflex coronary artery with subsequent reperfusion. The effect of ramiprilat on the recovery of postischemic wall thickening was shown to be through the bradykinin-mediated synthesis of prostacyclins, demonstrating the cardioprotective effects of ACE inhibitors on VD myocardial function.

Cardiac resynchronization therapy (CRT) is used for selected patients with advanced heart failure, improving heart failure symptoms, exercise capacity, and LV function.\textsuperscript{126} However, the effects of CRT vary significantly among individuals, and the observation that 20% to 30% of patients do not respond to CRT has resulted in a search for accurate predictors of response to this treatment.\textsuperscript{127} In a study of 51 patients with ischemic heart failure and LV dyssynchrony undergoing CRT, the response to CRT was directly related to the extent of viable myocardium and inversely related to the extent of scar tissue.\textsuperscript{128} Therefore, evaluation for VD myocardium and scar tissue may be considered in the patient selection process for CRT.

Several novel approaches are currently being sought in the treatment of VD myocardium. Neovascularization may be achieved through growth factors, such as endothelial nitric oxide synthase, fibroblast growth factor, and angiopoietin-1. Endothelial NOS is involved in the regulation of vascular tone and homeostasis by activating endothelial proliferation and inhibiting smooth muscle cell proliferation.\textsuperscript{129,130} In a swine model of VD myocardium, regional retroinfusion of endothelial NOS CDNA induced neovascularization via capillary proliferation and collateral vessel growth, resulting in improved functional reserve of VD myocardium.\textsuperscript{131} In addition, cardiomyocytes produce several different isoforms of fibroblast growth factor, and fibroblast growth factor-5 is a proto-oncogene known to promote angiogenesis in VD myocardium.\textsuperscript{132} Intracoronary injection of an adenoviral construct overexpressing fibroblast growth factor-5 has also been demonstrated to improve function of VD myocardium. Neovascularization may be achieved through growth factors, such as endothelial nitric oxide synthase, fibroblast growth factor, and angiopoietin-1.

Endothelial NOS is involved in the regulation of vascular tone and homeostasis by activating endothelial proliferation and inhibiting smooth muscle cell proliferation.\textsuperscript{129,130} In a swine model of VD myocardium, regional retroinfusion of endothelial NOS CDNA induced neovascularization via capillary proliferation and collateral vessel growth, resulting in improved functional reserve of VD myocardium.\textsuperscript{131} In addition, cardiomyocytes produce several different isoforms of fibroblast growth factor, and fibroblast growth factor-5 is a proto-oncogene known to promote angiogenesis in VD myocardium.\textsuperscript{132} Intracoronary injection of an adenoviral construct overexpressing fibroblast growth factor-5 has also been demonstrated to improve the function of VD myocardium in swine by stimulating myocyte number and hypertrophy.\textsuperscript{133,134} Finally, angiopoietin-1, first identified as the ligand for endothelial-specific TIE-2 (TEK tyrosine kinase endothelial) tyrosine receptor kinase, promotes endothelial cell sprouting and survival.\textsuperscript{135} In a swine model of chronic myocardial ischemia, injection of human angiopoietin-1 into the free wall of the compromised ventricle induced arteriogenesis with enhanced regional perfusion of VD myocardium.\textsuperscript{136} These studies suggest that neovascularization through therapeutic angiogenesis may have the potential to complement traditional revascularization techniques in the future.

In addition to neovascularization, stem cell therapy has been proposed as a novel therapeutic option for patients with VD myocardium. Mesenchymal stem cells have been shown to repair several injured tissues and improve LV function in animal models of myocardial infarction.\textsuperscript{137,138} In a swine model of chronic VD myocardium, intracoronary administration of mesenchymal stem cells improved function of the VD myocardium independent of coronary flow by stimulating myocyte proliferation and reducing cellular hypertrophy.\textsuperscript{139} Such a regression of cellular hypertrophy coupled with mesenchymal stem cell–mediated myocyte proliferation may potentially restore many of the contractile and metabolic alterations in VD myocardium. Recent clinical trials, such as the Transendocardial Autologous Cells in Ischemic Heart Failure Trial (TAC-HFT) and Cardiopoietic stem Cell therapy in heart failURE (C-CURE), have suggested that stem cell therapy may be a safe and effective option for the future treatment of heart failure, and potentially, VD myocardium.\textsuperscript{140,141}

**Limitations and Unresolved Questions**

The existence of VD myocardium has been shown convincingly in humans and in an array of animal models. As a result, molecular changes that take place in VD myocardium, including alterations in cardiomyocyte architecture, contractile myofibrils, calcium signaling, energy metabolism, and cytoprotective pathways, have been described. Many of these changes are similar in heart failure because of ischemic and nonischemic pathogeneses, suggesting that common mechanisms may be responsible for the depression in myocardial function. Reversal of several of these molecular pathways with mechanical unloading and correlation with improvements in cardiac function suggests that they may be amenable to pharmacological intervention and should be evaluated as potential targets for the treatment of heart failure. Yet, the development of specific therapies is hindered by the lack of mechanistic studies that delineate primary causative factors in the development of myocardial dysfunction with preserved myocyte viability. Moreover, technical differences in inducing VD myocardium in large animal models are likely to be responsible for discordance in many reported findings. However, despite these challenges in studying and targeting the changes occurring during the myocardial transition into dysfunction, the past decade has brought significant advances in our understanding of the molecular underpinnings of the VD heart. In the future, a systems biology approach to understanding VD myocardium would allow for an unbiased, integrative analysis of all the pathways impaired in this pathology, as opposed to focusing on the contributions of single molecular mechanisms.

**Conclusions**

VD myocardium is a well-established phenomenon. A large number of molecular changes have been reported for VD myocardium in humans, large animals, and mouse models. These include disruption of myocyte architecture, characterized by loss of myofibrils, glycogen accumulation, and changes in organelle morphology; altered expression and post-translational modifications of contractile proteins; alterations in calcium signaling and excitation–contraction coupling; suppression of mitochondrial oxidative phosphorylation with preservation of high energy phosphates and ATP-to-ADP ratio; and induction of cytoprotective genes. Altogether, a VD myocyte seems to require less energy to maintain its viability, likely as a protective response that counteracts the disrupting effects of perfusion mismatch in the setting of reduced coronary reserve. These abnormalities span both ischemic and nonischemic heart failure pathogeneses. Neovascularization, stem cell therapy, and advancements in surgical revascularization are promising areas of research that provide hope for improved clinical outcomes in patients with VD myocardium. Gaining further insights into the molecular mechanisms
responsible for the changes in VD myocardium, and subse-
quently targeting specific therapies individualized to such
anomalies, will allow for the development of additional
cardioprotective treatments aimed at the restoration of myo-
cardial functionality in patients with heart failure.

Sources of Funding
Dr Ardehali is supported by the National Institutes of Health Grants (K02 HL107448, R01 HL104181, and 1P01 HL108795). Dr Butler is supported by grants from National Institutes of Health, European Union, Health Resource Services Administration, Food and Drug Administration.

Disclosures
Dr Ardehali is a Consultant for Takeda and Cubist Pharmaceuticals. Dr Butler is a Consultant for Amgen, Bayer, Celladon, Gambro, GE Healthcare, Janssen, Medtronic, Novartis, Ono, Relypsa, Trevena, and has stock Options with Stemedica. Dr Gheorghiade has relation-
ship with the following companies: Abbott Laboratories, Astellas, AstraZeneca, Bayer Schering Pharma AG, Cardiorentis Ltd, CoThera, Cytokinetics, CytoPhex, Inc, DebioPharm S.A., Errekappra Terapeutici, GlaxoSmithKline, Iliara, Intersection Medical, Inc, Johnson & Johnson, Medtronic, Merck, Novartis Pharma AG, Ono Pharmaceuticals USA, Otsuka Pharmaceutical, Palatin Technologies, Pericor Therapeutics, Protein Design Laboratories, Sanofi-Aventis, Sigma Tau, Solvay Pharmaceuticals, Sticasres InterACT, Takeda Pharmaceutical North America, Inc, and Trevena Therapeutics and has received significant (>US$10000) support from Bayer Schering Pharma AG, DebioPharm S.A., Medtronic,Novartis Pharma AG, Otsuka Pharmaceuticals, Sigma Tau, Solvay Pharmaceuticals, Sticasres InterACT, and Takeda Pharmaceuticals North America, Inc. The other authors report no conflicts.

References
19. Knight C, Fox K. The vicious circle of ischemic left ventricular dysfunc-
tion. Am J Cardiol. 1995;75:106–10E.


45. Terracciano CM, Harding SE, Adamson D, Koban M, Tansley P, Birks EJ, Barton PJ, Yacoub MH. Changes in sarcolemmal Ca entry and sarcoplasmic reticulum Ca content in ventricular myocytes from patients with end-stage heart failure following myocardial recovery after combined pharmacological and ventricular assist device therapy. Eur Heart J. 2003;24:1329–1339.


127. Bax JJ, Bleeker GB, Marwick TH, Hoolek SB, Boersma E, Steendijk P, van der Wall EE, Schalij MJ. Left ventricular dyssynchrony predicts

**KEY WORDS**: calcium • heart failure • mitochondria
Molecular and Cellular Basis of Viable Dysfunctional Myocardium
Marina Bayeva, Konrad Teodor Sawicki, Javed Butler, Mihai Gheorghiade and Hossein Ardehali

Circ Heart Fail. 2014;7:680-691
doi: 10.1161/CIRCHEARTFAILURE.113.000912

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circheartfailure.ahajournals.org/content/7/4/680

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

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

Subscriptions: Information about subscribing to Circulation: Heart Failure is online at:
http://circheartfailure.ahajournals.org//subscriptions/