Metabolic Mechanisms in Heart Failure

Houman Ashrafian, MA, MRCP; Michael P. Frenneaux, MD, FRCP; Lionel H. Opie, MD, DPhil, FRCP

Abstract—Although neurohumoral antagonism has successfully reduced heart failure morbidity and mortality, the residual disability and death rate remains unacceptably high. Though abnormalities of myocardial metabolism are associated with heart failure, recent data suggest that heart failure may itself promote metabolic changes such as insulin resistance, in part through neurohumoral activation. A detrimental self-perpetuating cycle (heart failure → altered metabolism → heart failure) that promotes the progression of heart failure may thus be postulated. Accordingly, we review the cellular mechanisms and pathophysiology of altered metabolism and insulin resistance in heart failure. It is hypothesized that the ensuing detrimental myocardial energetic perturbations result from neurohumoral activation, increased adverse free fatty acid metabolism, decreased protective glucose metabolism, and in some cases insulin resistance. The result is depletion of myocardial ATP, phosphocreatine, and creatine kinase with decreased efficiency of mechanical work. On the basis of the mechanisms outlined, appropriate therapies to mitigate aberrant metabolism include intense neurohumoral antagonism, limitation of diuretics, correction of hypokalemia, exercise, and diet. We also discuss more novel mechanistic-based therapies to ameliorate metabolism and insulin resistance in heart failure. For example, metabolic modulators may optimize myocardial substrate utilization to improve cardiac function and exercise performance beyond standard care. The ultimate success of metabolic-based therapy will be manifest by its capacity further to lessen the residual mortality in heart failure. (Circulation. 2007;116:434-448.)

Key Words: fatty acids ■ glucose ■ heart failure ■ insulin resistance

Despite significant therapeutic advances, heart failure (HF) remains a leading cause of morbidity and mortality in developed1 and increasingly in developing countries,2 with a 5-year mortality rate of ~50%, which rivals or exceeds that of many cancers.3 This unacceptably high residual mortality and morbidity has mandated a reevaluation of cardiac biology with the aim to identify novel therapeutic strategies for HF. Because the daily turnover of ATP (~6 to 35 kg) is very many times that of the myocardial ATP pool, and even the healthy heart only extracts ~25% of energy derivable from substrates,4 it is not surprising that even subtle variations in the efficiency of energy generation or utilization may have a profound cumulative impact on cellular energy levels.5 Thus cardiac energetics in particular and metabolism in general represent promising targets for HF therapy.6

Correspondingly, numerous studies have identified decreased cardiac energy levels and flux as a consistent feature of HF.6,7 These observations have been reinforced by genomic studies8 and have focused considerable attention on metabolic modulation as a therapy for HF.6 Specifically, altered myocardial carbohydrate metabolism and the related state of myocardial insulin resistance (IR), in which given concentrations of insulin produce an attenuated glucose response,9 have attracted much interest as potential determinants of abnormal myocardial energetics. Even the earliest metabolic studies in diabetic patients by Bing and colleagues showed decreased myocardial glucose and increased fatty acid extraction.10 These excess fatty acids may adversely affect the myocardium11 and in HF may be associated with uncoupled respiration.12 However, the details of metabolic aberrations in HF are often indirect, preliminary, and sometimes conflicting. With the aid of recent clinical and molecular data, we will assess the hypothesis that the hyperadrenergic state of HF initiates an adverse metabolic vicious cycle,13 whereby aberrant metabolism and in some cases IR further detrimentally affect HF (Figure 1).13 After a critical review of the epidemiology and mechanisms of whether and how cardiac IR contributes to the more established role of myocardial metabolism in HF, we evaluate existing and novel metabolic and energetic therapies for HF.

Does Insulin Resistance Have a Role in the Pathogenesis of Heart Failure?

Is There an Epidemiological Relationship Between IR and HF?

A robust association exists between type 2 diabetes mellitus (T2DM), the ultimate manifestation of IR, and HF.14 The

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From the Department of Cardiovascular Medicine (H.A.), University of Oxford, Oxford, and the Department of Cardiovascular Medicine (M.P.F.), University of Birmingham, Edgbaston, UK; and the Hatter Institute for Cardiovascular Research (L.H.O.), Cape Heart Centre and Department of Medicine, University of Cape Town Faculty of Health Sciences, Cape Town, South Africa.

Correspondence to Dr Houman Ashrafian, Department of Cardiovascular Medicine, University of Oxford, John Radcliffe Hospital, Oxford OX3 9DU, UK. E-mail houman.ashrafian@cardiov.ox.ac.uk

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Framingham Study drew attention to the increased incidence (T2DM:control) of HF in diabetic men (2.4:1) and women (5:1) independent of age, coronary disease, hypertension, and body mass index. Although the risk of HF was exaggerated in the young, the prevalence of HF in elderly diabetic patients was as high as 30%. Other studies have shown that even a 1% increase in hemoglobin A1c enhances the risk of development of HF by 15%, that glucose is an independent predictor of hospitalization for HF and that stress-induced hyperglycemia, causes IR, Plasma FFA taken up by the heart is activated and transported by carnitine palmitoyltransferase-1 (CPT-1) into the mitochondria to uncouple respiration with oxygen wastage. These metabolic defects are added to other cellular consequences of the hyperadrenergic state, namely hyperphosphorylation of the sarcoplasmic reticulum and inhibition of the β-adrenergic receptor by increased glucose uptake by the heart and skeletal muscle, so that plasma glucose (PGlucose) increases (right) to promote formation of reactive oxygen species (ROS) that may inhibit glyceraldehyde-3-phosphate dehydrogenase (GAPDH); Multifactorial pancreatic damage, such as that mediated by FFA, together with hyperglycemia, causes IR, Plasma FFA increased plasma glucose levels are associated with the risk development of HF by 15%. Other studies have shown that even a 1% increase in hemoglobin A1c enhances the risk of development of HF by 15%. T2DM predisposes severe presentations of HF and predicts HF mortality; ≈25% of stable compared with >33% of patients with compensated HF manifest T2DM. In 1187 men prospectively assessed over 9 years, IR predicted the development of HF. A standard deviation decrease in insulin sensitivity increased the risk of HF by approximately one third.

This association may to a great extent be attributed to the confounding prevalence of hypertension, hyperglycemia, and associated free radical generation, microvascular dysfunction, and ischemic heart disease in IR states. However, although a tendentious diagnosis, the recognition of human diabetic cardiomyopathy as an entity characterized by the absence of coronary heart disease and hypertension but with ventricular and often diastolic dysfunction raises the hypothesis that IR, as a component of diabetic metabolism, could confer a detrimental metabolic effect on the myocardium.

Can IR Cause Cardiomyopathy?
A striking manifestation of the potentially causative relationship between IR and HF is the high prevalence of dilated cardiomyopathy and HF in clinical syndromes of IR. For example, Alström syndrome, a disorder that affects only 300 patients worldwide and is associated with severe IR, results in a potentially fatal cardiomyopathy in ≈60% of cases. Other genetic disorders such as Bardet-Biedl syndrome manifest obesity, IR, and cardiomyopathy. It might be argued that, in addition to their common feature of IR, these syndromes may contribute to cardiomyopathy through other mechanisms; importantly, however, as a corollary, in IR mice that develop genetic T2DM (db/db), IR is also associated with progressive cardiomyopathic changes.

Does HF Lead to IR?
Although evidence is increasing that IR predisposes to HF, preliminary evidence also suggests that HF may reciprocally predispose to IR and T2DM. Glucose abnormalities are overrepresented in HF as they are identified in 43% of HF patients, and these abnormalities correlate with increasing levels of circulating norepinephrine and with decreasing functional status. Studies that apply the euglycemic-hyperinsulinemic clamp to patients with HF support these snapshot observations; irrespective of the inciting cause, HF is associated with systemic IR that itself predicts increased mortality. It is important not to assume that systemic and myocardial IR invariably coexist; for example, T2DM patients with apparently normal ventricular function manifest a competent myocardial insulin response that contrasts with increased systemic IR. By contrast in HF, both systemic and myocardial IR may increase. This proposal is based on positron emission tomographic (PET) observations that the HF myocardium has reduced glucose uptake in favor of fatty acid uptake but not all studies. HF predicts the development of T2DM in a graded way. In 7.7 years of follow-up, T2DM developed in 13% of New York Heart Association (NYHA) class I, 15% of NYHA class II, and 20% of NYHA class III HF patients. The risk of T2DM in HF is 18% to 22% higher per 10 years than in treated hypertension. PET studies remain necessarily indirect because of their capacity to quantify myocardial substrate uptake rather than the related but dissociable details of substrate utilization.
With these limitations acknowledged, myocardial glucose uptake measured by PET appears to be lower in diabetic (0.34 \( \mu \text{mol} \cdot \text{min}^{-1} \cdot \text{g}^{-1} \)) than in nondiabetic patients (0.47 \( \mu \text{mol} \cdot \text{min}^{-1} \cdot \text{g}^{-1} \)) with coronary artery disease and HF.\(^{45}\) Both are lower than historical control subjects (0.61 \( \mu \text{mol} \cdot \text{min}^{-1} \cdot \text{g}^{-1} \)). This implies that HF, particularly in the context of coronary disease, is associated with myocardial IR. As a corollary, preliminary evidence suggests that glucagon-like peptide 1, which increases plasma insulin levels and decreases glucose levels and thus mitigates IR, also ameliorates HF.\(^{46}\)

**Limitations**

An explicit weakness of epidemiological studies is their inability to fully account for confounders such as traditional risk factors, reverse causation (whereby underlying preexisting IR was unmasked by advancing HF) or for diuretic-induced diabetes (the worse the HF, the greater the need for diuretics). The above studies cannot therefore be regarded as mechanistic but are hypothesis generating. Whereas the clinical and laboratory evidence presented here and elsewhere supports a contributory role for T2DM and probably IR in HF,\(^{24–31}\) a reciprocal causal relation whereby HF also promotes IR remains largely associative and hence more speculative.\(^{47}\) Nevertheless, the role of HF in the promotion of IR is mechanistically supported in a canine model of cardiomyopathy that develops systemic and myocardial IR.\(^{48}\) More studies are clearly needed.

**The Role of Myocardial Metabolism in Relating Insulin Resistance to Heart Failure**

A number of compatible proposals to explain the associations between altered metabolism, IR, and HF include: (a) activation of the neurohumoral system, which includes the sympathetic nervous system (SNS) and the renin-angiotensin-aldosterone system (Figure 2)\(^{20–49}\); (b) inflammation as exemplified by increased tumor necrosis factor \( \alpha \) levels and its soluble receptors\(^{50}\); (c) alterations in skeletal muscle function and mass as a result of reduced physical activity; (d) endothelial dysfunction; (e) increased adipokines such as adiponectin and leptin\(^{51}\); and (f) pharmacological exacerbation of IR (eg, by diuretics). Of these, (a) remains the best investigated and probably most robust contributor to altered metabolism in HF.

**Adrenergic Mechanisms That Underlie Altered Myocardial Metabolism and IR in HF**

Neurohumoral homeostasis is maladaptively activated in response to a chronic reduction in cardiac output as characterized by persistent activation of the SNS and the interlinked renin-angiotensin-aldosterone system.\(^{52}\) In addition to this increased catecholamine secretion, reduced cardiac catecholamine reuptake can be observed.\(^{53}\) Increased catecholamines have directly detrimental effects on the heart, which cause marked enzyme loss as an index of diffuse myocardial damage, and substantial oxygen-wastage even in the absence of free fatty acids (FFA) in the perfusate.\(^{54}\) Furthermore, norepinephrine promotes both coronary vasoconstriction\(^{20}\) and increased plasma FFA levels,\(^{55}\) which further promote oxygen-wastage (Figure 3).\(^{56}\) Infusion studies in volunteers support a role for increased norepinephrine levels in HF as a cause of elevated plasma FFA.\(^{57}\) In turn, FFAs reciprocally augment SNS activity, at least in normal controls.\(^{58}\) In human skeletal muscle, a dose-response relationship exists between plasma FFA\(^{27,59,60,61}\) and defects in insulin signaling.\(^{62}\) This may in part be caused by FFA-mediated activation of protein kinase C-\( \beta \), which phosphorylates insulin receptors and results in reduced capillary opening and reduced myocyte glucose import.\(^{63,64}\) Acute decreases in FFA levels in humans increase glucose uptake and decrease IR.\(^{57}\) Importantly, IR can contribute to this aberrant metabolism; independent of other risk factors for cardiac dysfunction, a study of IR obese young women represents strong evidence that IR per se can increase cardiac FFA metabolism and decrease myocardial contractile efficiency.\(^{27,60}\) According to this schema, because myocyte FFA metabolism is proportional to plasma FFAs, myocardial FFA metabolism should increase in HF (a frequent though not consistent finding).\(^{41,65}\)

Locally increased cardiac SNS activity in HF is also important. With use of PET with a norepinephrine analog and \(^{18}\)F-fluorodeoxyglucose, myocardial segments with left ventricular (LV) dysfunction have reduced presynaptic norepinephrine reuptake and myocardial glucose uptake in relation to less impaired myocardial segments in the same patients.\(^{66}\) Thus, after control for confounding variables, altered metabolism and IR directly relate to local SNS activity.

Thus, activation of the SNS by both catecholamines and the renin-angiotensin-aldosterone system both centrally and peripherally,\(^{52}\) directly and through increased plasma FFA, is...
to the nuclear receptor peroxisome proliferator activator receptor α (PPAR-α).68 Which of these are pertinent and proximate rather than downstream to IR?

Although a robust association exists between muscular triglyceride content and IR,67 it is unclear whether the lipid species that mediates IR is triglyceride or intracellular fatty acid and its metabolites. The mobilization of FFA from triglyceride is determined by adiposome triglyceride lipase. In adipose triglyceride lipase–null mice, despite the lack of triglyceride, the reduced availability of lipase-derived FFAs increased glucose utilization and decreased cardiac IR.69 Thus, at least in transgenic mice, FFAs and their intracellular derivatives rather than triglycerides appear to be critical in the mediation of cardiac IR either by alteration of insulin signaling28 or by direct competition with glucose metabolism. Accumulation of intramuscular fatty acyl coenzyme A (acyl CoA), a FFA that is activated after uptake, then inhibits intracellular muscle insulin signaling, which thereby limits glucose uptake (Figure 3).67

**Consequences of Metabolic Disturbances in Heart Failure**

Accordingly, one of the most profound consequences of contractile dysfunction and SNS activation in HF is altered metabolism. The pertinence of the ensuing energy deficiency in HF has recently been underlined by extensive advances in noninvasive imaging technology.4,6,7 In this section, the energy changes that occur in HF in vivo are detailed, the contribution of altered substrate utilization to this energy deficiency is discussed, and how the cardiac transcriptional milieu contributes to these changes is reviewed. The limitations of energetic and utilization studies are discussed in detail. Ultimately, these mechanistic insights will set the scene on how to affect HF with metabolic therapy.

**High-Energy Phosphates**

Both the failing heart7 and the IR myocardium are energy deficient. This precarious energy state is unsurprising when it is considered that even in the healthy heart only ~25% of energy derivable from substrates is converted to useful external work.4,70 This is further exacerbated by the astonishing requirement that the heart needs to generate up to ~70 times its own weight in ATP everyday.5 Robust biochemical evidence has existed for decades that the failing myocardium is energy deficient: the ratio of [ATP]/[ADP][Pi], based on the Gibbs law, determines the energy charge of the heart and hence the capacity to perform work. Early data from limited human myocardial biopsy specimens obtained during surgery or derived during cardiac transplantation demonstrated that the failing heart had ~30% lower ATP level than controls.6 Although this confirmed that the failing heart is indeed depleted of energy, extensive biochemical and later magnetic resonance spectroscopy studies have nevertheless failed to provide a compelling causal relation between such energy deficiency and HF.6 Magnetic resonance spectroscopy has revolutionized the study of cardiac energy metabolism in that many studies have confirmed energy deficiency in HF (detailed in an excellent review by Neubauer);7 however, one criticism of both biopsy and magnetic resonance spectro-
substrate utilization. Except in the postprandial period, the heart principally metabolizes FFAs (up to 70%).65 Glucose and other carbohydrates such as lactate represent much of the remaining substrate. Mitochondrial oxidative phosphorylation represents the major source of energy (>95%). Being omnivorous renders the heart remarkably adept in the maintenance of its energy levels despite widely varying energy requirements, but this ability comes at a cost.66 Fatty acid oxidation (FAO) requires greater oxygen for a given quantity of ATP synthesis than do carbohydrates. Thus, for the fully metabolized molecule of oleate, the major FFA taken up by the human heart, we calculate that 2.8 molecules of ATP are produced per oxygen atom utilized as opposed to 3.17 for carbohydrate. At first glance, this represents only a meager 11% increase in energy produced per oxygen (Table 1); the real difference may be greater.54,75 In pigs, a switch from maximal glucose to maximal FFA utilization increased the oxygen requirement by 50%.76 In dogs, the myocardial oxygen uptake on adrenergic challenge rose by 60%, of which approximately two thirds was mediated by FFA.77 Hearts from IR obese mice had decreased metabolic efficiency, as manifested by a 27% increase in unloaded oxygen uptake.78 Although these observations reflect unphysiological metabolic shifts, they may be relevant to the hyperadrenergic HF state, especially during an exercise-induced catecholamine surge that could provoke FFA-induced futile cycling and uncoupling (Figure 5). Proof of this supposition would require measurements of FAO and myocardial oxygen uptake in HF during exercise.

The integrity of the mitochondrial membrane is central to the efficiency of energy generation. Uncoupling proteins (UCPs) and the adenine nucleotide translocator lower the proton gradient in that they allow protons to re-enter the mitochondrial matrix (leak) with the production of heat rather than ATP.

Table 1. Effect on ATP-to-Oxygen Ratio of a Total Change From Glucose to FFA Utilization by Myocardium

<table>
<thead>
<tr>
<th>Molecule</th>
<th>ATP Yield per Molecule</th>
<th>ATP Yield per Carbon Atom</th>
<th>ATP Yield per Oxygen Atom Taken Up, P/O Ratio</th>
<th>Relative Decreased ATP Production Efficiency per Unit Oxygen if Glucose Is Substituted by FFA, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose (C6)</td>
<td>38</td>
<td>6.33</td>
<td>3.17</td>
<td>0</td>
</tr>
<tr>
<td>Palmitate (C16)</td>
<td>129</td>
<td>8.06</td>
<td>2.80</td>
<td>11.7</td>
</tr>
<tr>
<td>Oleate (C18)</td>
<td>144</td>
<td>8.00</td>
<td>2.82</td>
<td>11.0</td>
</tr>
</tbody>
</table>
in more detail. Inhibition of FFA transport into the myocardium may cause further energy loss.65 Although only preliminary evidence exists for the role of UCPs in cardiac tissue, UCPs do appear to be upregulated in human HF.12 The combination of increased UCP and other UCPs (eg, adenine nucleotide translocator) may render the myocardium inefficient when FFA is predominantly used as fuel. This sequence is at present best viewed as speculative but has preliminary support in the diabetic rodent heart.80

The precise nature of substrate utilization in cardiac health and disease is controversial; this is in part caused by the limitations of even the most sophisticated tools (eg, substrate labeling and assessment with carbon-13 nuclear magnetic resonance spectroscopy) and in part caused by the indirect nature of human studies.4 These substrate studies should thus be interpreted judiciously. For example, in rodent LVH, a reduction in PPAR-α81 may explain the observed reduced FFA metabolism. In the spontaneously hypertensive rat (SHR), a defect in FFA transporter (CD36) and reduced FFA utilization may reflect a model-specific defect rather than a general feature of LVH.82 Nevertheless, in LVH a shift away from FFA metabolism to carbohydrate metabolism (such as anaplerosis) seems to occur.83,84

Although subject to the limitations and controversies of data from diverse animal models of HF, indirect studies, and heterogeneous clinical settings, HF as a state of SNS activation may result in increased plasma FFA and hence predispose to IR. Accordingly, in mild to moderate HF, the myocardium appears to utilize FFA as its predominant substrate.65,85 Studies in skeletal muscle suggest that plasma FFAs inhibit glucose transport/phosphorylation as well as muscle glycogen synthesis and glucose oxidation86; similar mechanisms may explain the effect of FFA in the decrease in myocardial glucose metabolism.87 Activated FFA as acyl CoA is transported into the mitochondria by the enzyme carnitine palmitoyl transferase-1 (Figure 5), which is subject to feedback inhibition by the acyl CoA breakdown product malonyl CoA that builds up during high rates of FAO. This negative feedback reduces FAO and further increases cytoplasmic FFA and acyl CoA metabolites. In advanced HF, this unfavorable metabolic profile is complicated by the down-regulation of FAO as driven by reduced PPAR-α99–97 and impaired mitochondrial oxidative capacity,98 that results in metabolic inflexibility91 and catastrophic energy deficiency, especially if FFA is abruptly reduced.92 It is important to note that uncertainty exists with regard to the generalizability of substrate use findings; eg, some investigators have demonstrated increased PPAR-α and FFA in advanced HF.42,93 Furthermore, it is unclear whether substrate alterations are adaptive and whether/when they become maladaptive. This uncertainty reflects a dearth of human studies that examine the prospective changes in substrate use and incapacity specifically to manipulate this utilization in the progression of HF. Nevertheless, it appears that early inhibition of inefficient FAO is a good target to improve metabolic profile and prognosis of HF.65

The Role of Transcription Factors in Metabolism

Modulation in HF

Regulation of FAO is modulated by a variety of influences, such as an important gene transcriptional component, especially by the PPAR family of transcription factors. As mentioned above, PPARs, especially PPAR-α, and their co-activators are modified by lipid moieties and provide attractive targets for therapeutic intervention.84 It is generally, although not universally, considered that PPAR-α is down-regulated in advanced HF as noted above and that its pharmacological upregulation after pressure overload or ischemia hastens the development of HF.94

In addition to alterations in FAO under the influence of PPAR-α, human HF is associated with small aberrant mitochondrial structure and function, especially PPAR-γ coactivator 1α (PGC-1α).96–99 Not only is HF associated with increased oxidative capacity, but with decreased PGC-1α, as well.100 Mice hearts that lack PGC-1α are predisposed to develop HF in response to pressure overload and can be rescued by restitution of PGC-1α activity.101 Thus PGC-1α, among other transcription factors, has a critical role in modification of the heart’s response to metabolic stress. Induction of PGC-1α might therefore be
presumed to improve HF; indeed, “it will therefore be of great interest to develop small molecules with pharmaceutical potential that can increase PGC-1α activity in vivo”.101 However, profound cardiac induction of PGC-1α in some animal models results in cardiomyopathy, perhaps in part as a result of myofibrillar apparatus displacement by increased mitochondria.102,103 Moreover, short-term induction of PGC-1α resulted in reversible contractile dysfunction.103 Pertinently, PGC-1α expression in myoblast cell lines led to the mitochondrial uncoupling, which resulted in decreased ATP formation and heat production.104

The seeming paradox that HF results from models that either profoundly upregulate or downregulate the same metabolic mediator (eg, creatine kinase, PPAR-α, or PGC-1α), provides a salutary note that cardiac metabolism in health and disease is exquisitely balanced. As with all transgenic models, models of metabolic manipulation are prone to methodological and interpretative challenges.105 For example, PPAR-α has been either greatly overexpressed in the heart by use of the powerful myosin heavy chain promoter or it has been knocked out. Both animal models develop systolic dysfunction and respond poorly to stress (the former’s phenotype is greatly exacerbated by a high-fat diet).94 Factors such as the transgenic construct (even the same promoter gene constructs respond differently in different models; eg, because of the differing site of transgene integration), the tissue specificity of transgene expression (ie, local or systemic), and the stresses imposed have a profound impact on the phenotype.105 These animals do not behave physiologically; metabolic lessons derived from these transgenics to general HF should accordingly be generalized with due care.94 Moreover, the impact of transcription factor modification in tissues other than the heart should be considered; eg, PPAR-α agonists exhibit limited effects on myocardial target genes; the peripheral actions of PPAR-α ligands may explain many resulting cardiac effects.94

Much remains unknown about the adaptive and maladaptive impact of transcription factor modification in HF; thus PGC-1α enhances mitochondrial biogenesis (presumed to be beneficial) but also enhances FAO and mitochondrial uncoupling through UCPs.106 Depending on the degree and timing of activation and the tissues in which it is activated, PGC-1α activation may prove adaptive or maladaptive. Similarly, although FAO is generally considered undesirable in HF, FFA yield more energy per unit of carbon than carbohydrates. It is conceivable that under some circumstances (eg, in the healthy heart) this increased energy density is desirable. Thus, when therapeutic inhibition of FAO, increased glucose metabolism, increased creatine transport, or enhanced PGC-1α is attempted, moderate rather than dramatic modifications in metabolic function should be sought.106

Role of Ketones in HF

HF has some metabolic similarities to starvation and to diabetes mellitus (“starvation in the midst of plenty”). In starvation, the liver converts plentiful FFA to the ketone bodies (KBS) acetoacetate and 3-hydroxybutyrate. HF promotes ketogenesis by the liver and increases plasma KBS.107–109 Because KBS are converted rapidly and in a concentration-dependent manner to acetyl CoA by the heart, the 2-fold increased plasma KBS in HF suggests that HF mitochondria are replete with KB-derived acetyl CoA. This is rendered even more plausible by studies that suggest that KBS are the normal rodent heart’s preferred substrate.110–112 Experimentally, increased levels of KBS may block the citrate cycle to cause contractile dysfunction.9 When added to myocytes, concurrent inhibition of glucose and FAO,65 through inhibition of glycolysis and of AMP-activated protein kinase (AMPK), occurs (Figure 3). KBS could stranglecardiac energy supplies, reduce glucose metabolism, alter signaling, and induce IR.113 Manipulation of KB synthesis may represent one of the many noncardiac benefits of therapeutic metabolic modification. Hepatic carnitine palmitoyl transferase-1 represents the most regulated step in ketogenesis and its inhibition potentially increases myocardial energy supply (Figure 5).114

A Rational Metabolic Approach to Treatment of Heart Failure

To recapitulate, neurohumoral activation in HF thus results in increased FFA metabolism with some evidence for systemic and myocardial IR. These changes may have detrimental effects on myocardial energetics. A vicious cycle that involves IR (Figure 1) includes multiple therapeutic nodes that may be targeted in HF (Table 2 and Figures 3 and 5).

Neurohumoral Antagonism

Neurohumoral modification is the standard of care in HF.115 Angiotensin-converting enzyme inhibitors and angiotensin receptor blockers have significantly reduced the incidence of T2DM in patients with HF.116,117 Of specific interest, enalapril prevented diabetes in those with IR (defined by a fasting plasma glucose ≥6.1 mmol/L) in a post hoc analysis.116 Experimentally, these agents act by protection of β-pancreatic cells.118,119 β-Blockers are pro-IR agents, with the exception of the α-β-blocker carvedilol.20 Note that bisoprolol and nebivolol are still untested in relation to IR. In dogs with dilated cardiomyopathy, carvedilol but not metoprolol reduced circulating FFA, decreased myocardial FFA uptake, and increased glucose uptake.120,121 This substrate switch was accompanied by increased stroke volume and decreased LV end-diastolic pressure. Similarly, carvedilol reduced myocardial FFA extraction between 20% and 60% in patients with HF.120,121 Metoprolol, a cardioselective β-blocker, failed to decrease myocardial FFA uptake.121 In another study, carvedilol decreased myocardial FFA use as assessed by PET while ejection fraction increased.121 These metabolic effects of carvedilol may contribute to its remarkable clinical success in the therapy of HF.

Increasing Glucose Metabolism

Although insulin increases glucose utilization, the complications of long-term parenteral therapy and the risks of hypoglycemia render insulin an unattractive therapy. Nonetheless, as proof of principle, the application of glucose-insulin-potassium to patients with chronic ischemic cardiomyopathy lessened ventricular dysfunction.122 AMPK is the cells’ energy sensor and a critical metabolic regulator. It stimulates
TABLE 2. The Targets and Their Corresponding Therapeutic Agents for the Metabolic Modification of Insulin Resistance in Heart Failure

<table>
<thead>
<tr>
<th>Target</th>
<th>Treatment</th>
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<tr>
<td>Inhibition of neurohumoral activation</td>
<td>ACE-inhibitors, angiotensin-II receptor blockers, aldosterone antagonists, and β-blockers (carvedilol)</td>
</tr>
<tr>
<td></td>
<td>Pharmacological induction of vagus-like activity</td>
</tr>
<tr>
<td>Increasing glucose metabolism</td>
<td>Existing: exercise, metformin, insulin, glucagon-like peptide-1, dipeptidyl peptidase IV inhibitors</td>
</tr>
<tr>
<td></td>
<td>Future: new AMP-activated protein kinase agonists and pyruvate derivatives</td>
</tr>
<tr>
<td>Reducing FA metabolism</td>
<td>Existing: exercise, insulin, glucagon-like peptide-1, dipeptidyl peptidase IV inhibitors, perhexiline, trimetazidine</td>
</tr>
<tr>
<td>Reducing IR</td>
<td>Glucagon-like peptide-1, dipeptidyl peptidase IV inhibitors, thiazolidinediones (glitazones) and biguanides (eg, metformin)</td>
</tr>
<tr>
<td>Increasing mitochondrial volume (total cellular energetic capacity)</td>
<td>Future: PPAR-γ coactivator-1α agonists, nitric oxide augmentation, cyclic guanosine monophosphate augmentation (eg, sildenafil and other type-5 phosphodiesterase inhibitors)</td>
</tr>
<tr>
<td>Reducing cellular energy demand</td>
<td>Existing: β-blockers, ranolazine and cardiac resynchronization therapy</td>
</tr>
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While these agents have explicit and unequivocal metabolic benefits, a dearth of clinical trials exists in this area. None of these agents is yet indicated specifically for the treatment of insulin resistance in heart failure.

Insulin Sensitization

Metformin is an insulin sensitizer that works in part through AMPK stimulants such as exercise and adiponectin are promising candidates to treat HF in that they increase glucose utilization.123,124

PPAR-γ Agonists

On theoretical grounds, potent insulin-sensitizing agents such as rosiglitazone and pioglitazone might be expected to be particularly beneficial in HF. Yet, because of the capacity of PPAR-γ agonists to increase fluid accumulation, a risk that they might exacerbate HF is perceived. Accordingly, these agents have often been regarded as contraindicated or at least to be used with caution, even in diabetic patients with HF.129

A retrospective series from the Cleveland Clinic concluded that diabetic individuals with prior HF who were given glitazones had less evidence of central fluid retention than nonusers.130 PPAR-γ agonists increase fluid accumulation by an increase of renal tubular fluid retention; the consequent edema, at least in animals, can be mitigated with amiloride, a diuretic that selectively inhibits sodium reabsorption in the collecting duct.131,132 Although studies such as the Prospective Pioglitazone Clinical Trial in Macrovascular Events (PROaCTive) Study have suggested an increased incidence of HF that required hospitalization in patients treated with PPAR-γ agonists, no clear and centrally adjudicated definition of HF was provided.133 In early HF at least, robust trial data would suggest that such fluid accumulation does not seem to correlate with deteriorating cardiac function.134 Nonetheless, recent meta-analysis of 42 trials suggests that rosiglitazone given for T2DM has serious cardiovascular side effects.135 Final judgment on the benefits or detriments of PPAR-γ agonists in HF may best be reserved until after the results of the Rosiglitazone Evaluated for Cardiac Outcomes and Regulation of Glycemia in Diabetes (RECORD) trial, which is specifically designed to assess cardiovascular outcomes with rosiglitazone, are shared.136 especially in the light of the improved LV function in a dog model of HF induced by mitral regurgitation.137

Decrease of Fatty Acid Metabolism by Fatty Acid Oxidation Inhibitors

Trimetazidine is the first agent shown to reduce myocardial FAO in humans (Tuunanen et al, unpublished data, 2007). The precise mechanism by which trimetazidine partially inhibits FAO remains controversial; some investigators advocate a selective inhibition of long-chain 3-ketoacyl CoA thiolase,139 whereas other investigators reject this.140 Trimetazidine has additional effects,141 such as mitochondrial protection,142 lessened proton production,143 and endothelial protection.144 Thus, although trimetazidine has in part delivered on the promise of metabolic modulation in human HF (Table 3),138,145–155 it is unlikely to be marketed for HF because of patent issues.156 A greater improvement in HF might be expected by perhexiline, a reversible carnitine palmitoyl transferase-1 inhibitor (Figure 5) that putatively reduces mitochondrial FFA transport.157 Introduced in the 1970s as an effective antianginal agent, use of perhexiline diminished after unexplained cases of hepatic failure and neuropathy were caused by high plasma concentrations in poor perhexiline metabolizers.158 The fact that these side effects are easily avoided by dose titration of plasma levels has led to its renaissance for refractory angina in Australia and New Zealand with restricted use in Europe.159 In a randomized, double-blinded study of 56 optimally medicated HF patients over 8 weeks, perhexiline improved symptoms, peak exercise
oxygen uptake, and LV function (relative improvement of ≈40%). Although these preliminary data are promising, prospective prognostic trials are needed to prove the capacity of perhexiline to improve HF. Moreover, although it is thought that perhexiline reduces myocardial FAO and improves glucose and lactate metabolism, this remains to be shown in patients.

Other Potential Therapies

Although as yet no agents exist that promote mitochondrial biogenesis, PGC-1α has generated interest. The nitric oxide-cGMP–dependent pathway may also control mitochondrial biogenesis (Table 3). If confirmed, the application of nitric oxide technology may ameliorate energy deficiency in HF. Indeed, phosphodiesterase 5 inhibitors such as sildenafil that increase cGMP have in preliminary studies improved LV function and exercise capacity in HF.

Diuretics stimulate renin-angiotensin-aldosterone system and appear to promote IR; they may adversely affect myocardial metabolism. In an observational study of HF patients, loop diuretic use was an independent predictor of mortality. In a retrospective analysis, chronic diuretic therapy was associated with increased mortality. Hence, unless prospective randomized trials prove otherwise, diuretics should be given for HF only when fluid retention is present. Potassium depletion, which predisposes to diabetes, must be avoided.

Cardiac resynchronization therapy lessens morbidity and mortality in advanced HF. By reduction of the inefficiency of dyscoordinate ventricular contractions, cardiac resynchronization therapy increases glucose metabolism and reduces IR to improve cardiac efficiency and cardiac energetics. Statins lessen the incidence of new diabetes in patients with metabolic syndrome, improve glucose tolerance, and improve HF. A plausible mechanism may be through activation of AMPK. Even interventions that are seemingly unrelated to energetics, such as continuous positive airway pressure, may ameliorate energy efficiency.

Exercise and Dietary Modification

Even when mobilization of insulin-sensitive glucose transporter (GLUT) 4 vesicles to the sarcolemma is indirectly blocked by high FFA, other vesicles are still sensitive to exercise. In obese subjects, short-term exercise improves insulin-mediated perfusion of skeletal muscle and glucose delivery. In HF, exercise training reduces IR consonant with its effect in the increase in skeletal and cardiac glucose uptake. The latter increase occurs in HF despite unchanged insulin signaling; the likely mechanism is by stimulation of the insulin insensitive GLUT-1 transporters.

Existing and Future Clinical Applications of Metabolic Modulation in HF

Existing Treatments

As reviewed herein, the association and possible causative role of aberrant metabolism in HF has only recently come to the foreground. Accordingly, no definitive data exist that show the incontrovertible benefit of any one therapy for the correction of abnormal metabolism. On the basis of the preceding discussion it appears that existing standard practice

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**TABLE 3. The Results of Clinical Trials With Partial Fatty Oxidation Inhibitors**

<table>
<thead>
<tr>
<th>Drug</th>
<th>Condition</th>
<th>No. of Patients Treated (Daily Dose)</th>
<th>Length of Treatment, Months</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pooled trimetazidine studies</td>
<td>Ischaemic LV dysfunction</td>
<td>95 placebo and 91 (20 mg × 3 trimetazidine)</td>
<td>6</td>
<td>Improved symptoms, exercise tolerance, and LVEF.</td>
</tr>
<tr>
<td>Trimetazidine</td>
<td>All-cause LV dysfunction</td>
<td>12 (20 mg × 3 trimetazidine)</td>
<td>3</td>
<td>Improved symptoms, exercise, LVEF from 33% to 39% (placebo fell from 36% to 33%), and PCr/ATP ratio by 33%.</td>
</tr>
<tr>
<td>Trimetazidine</td>
<td>All-cause LV dysfunction</td>
<td>27 placebo and 28 (20 mg × 3 times trimetazidine)</td>
<td>13</td>
<td>Improved symptoms, exercise tolerance, and LVEF from 34 to 41% (placebo fell from 36 to 34%).</td>
</tr>
<tr>
<td>Trimetazidine</td>
<td>Non-ischemic Cardiomyopathy</td>
<td>7 placebo and 12 (20 mg × 3 trimetazidine)</td>
<td>3</td>
<td>LVEF from 30.9% to 34.8% (placebo fell from 37.5% to 31.9%). Reduced FAO. Improved IR.</td>
</tr>
<tr>
<td>Etomoxir</td>
<td>All-cause LV dysfunction</td>
<td>10 (80 mg etomoxir)</td>
<td>3</td>
<td>Improved symptoms and LVEF from 22% to 27%</td>
</tr>
<tr>
<td>Etomoxir</td>
<td>All-cause LV dysfunction</td>
<td>121 placebo, 118 (40 mg) and 108 (80 mg) etomoxir</td>
<td>6</td>
<td>No change in symptoms or EF. Increased incidence of hepatotoxicity</td>
</tr>
<tr>
<td>Perhexiline</td>
<td>All-cause LV dysfunction</td>
<td>28 placebo and 28 (dose titrated perhexiline)</td>
<td>3</td>
<td>Improved symptoms, MVO2 (16.1 to 18.8 mL·kg⁻¹·min⁻¹, Minnesota quality of life score and LVEF fraction from 24% to 34%)</td>
</tr>
</tbody>
</table>

Note: In this table some of the trimetazidine trials have been evaluated in combination.
with therapies that include high doses of an angiotensin-converting enzyme inhibitors, angiotensin receptor blockers, or both, as well as β-blockers with preferential use of the α-β-blocker carvedilol, may help restore metabolic normality. Unnecessary diuretics must be avoided except in fluid overload. In light of promising preliminary evidence, metformin should be tested in HF (some authorities propose a revocation of the current contraindication in HF), especially with exercise training. Although evidence exists to suggest that thiazolidinediones may not be deleterious in HF,24,134 this contrasts with recent studies that suggest adverse cardiovascular outcomes in patients with T2DM135,136 and an existing consensus statement from the American Heart Association and the American Diabetes Association that recommends caution in prescription of thiazolidinediones in those with NYHA class I and NYHA II HF and complete avoidance of thiazolidinediones in patients with NYHA class III and NYHA IV HF.186 Increasing controversy surrounds the use of thiazolidinediones in T2DM patients and at present thiazolidinediones should be used in HF with great caution until the publication of appropriate trial evidence specific to HF. Finally, although not yet supported by definitive evidence, we propose that a specific goal in HF should be prevention and treatment of IR, preexisting and new T2DM as assessed, albeit relatively bluntly, by serial fasting plasma glucose and perhaps homeostasis model assessment values.187 Although many questions remain with regard to the role of metabolism in HF (Table 4), a number of exciting future prospects promise to contribute to the amelioration of HF prognosis through metabolic modulation, subject to further research and trials.

Future Prospects

Insulin Sensitization

Whereas tight glycemic control, such optimal insulin dosing, is strongly advocated in diabetic patients, insulin is neither practical nor supported by evidence in nondiabetic HF patients. However, novel insulin-sensitizing agents developed for the treatment of diabetes and effective in amelioration of metabolic profile may also prove effective in HF. Glucagon-like peptide, a gut-derived incretin hormone, promotes insulin secretion and sensitization, was effective in preliminary HF trials, and will be further investigated.46,128 Inhibitors of glucagon-like peptide degradation include dipeptidyl peptidase-4 inhibitors.188 Augmented AMPK signaling (through exercise, metformin, and statins) promotes insulin sensitization. In animal models, adiponectin deficiency leads to HF, especially during pressure overload,189 which may be mediated via impaired AMPK signaling and glucose metabolism.190 Conversely, small-molecule AMPK agonists may improve HF.123

Substrate Modification

Improvements in cardiac substrate profile may reverse any existing IR of HF associated with improved cardiac energetics, LV function, and amelioration of the morbidity and mortality of HF. Further HF trials with promising metabolic modulators such as trimetazidine and perhexiline should be initiated to include IR and new diabetes as prespecified end points. In consideration of their provenance and well-understood chemistries, these agents are more likely to be more cost-effective for both the developed and developing world than novel therapies.

Kinase Modification

Although existing agents such as β-blockers and angiotensin-converting enzyme inhibitors have proven effective in HF, centrally acting sympatholytics such as moxonidine have failed, apparently inexplicably.191 It is the α1-adrenoreceptors through which these agents act that are dysregulated by increased expression and activity of G-protein–coupled receptor kinase 2 in the adrenal gland.192 Inhibition of this

<table>
<thead>
<tr>
<th>TABLE 4. Questions Yet to be Definitively Answered Relating to the Metabolic Modification of Heart Failure</th>
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<tbody>
<tr>
<td>Neurohumoral activation</td>
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<tr>
<td>Glucose metabolism</td>
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kinase and/or those that act on the β-adrenergic receptor may further decrease adrenergic activation to ameliorate metabolic abnormalities.193

Disclosures
Dr Srenfexes and Ashrafian have applied for a patent for the use of perhexiline in HF. Dr Srenfexes is on the clinical end points committee for 2 heart failure trials funded by Menarini (Seniors) and Beautiful (Servier). He has received support to attend international meetings from Novartis, Pfizer, AstraZeneca, and Servier. Dr Opie has given lectures for Servier, the manufacturer of trimetazidine.

References


68. Pettersen K, Shulman GI. New insights into the pathogenesis of insulin resistance in humans using magnetic resonance spectroscopy. Obesity. 2006;14:345–40S.


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