Cardiac Metabolism and its Interactions With Contraction, Growth, and Survival of Cardiomyocytes

Stephen C. Kolwicz Jr, Suneet Purohit, Rong Tian

Abstract: The network for cardiac fuel metabolism contains intricate sets of interacting pathways that result in both ATP-producing and non–ATP-producing end points for each class of energy substrates. The most salient feature of the network is the metabolic flexibility demonstrated in response to various stimuli, including developmental changes and nutritional status. The heart is also capable of remodeling the metabolic pathways in chronic pathophysiological conditions, which results in modulations of myocardial energetics and contractile function. In a quest to understand the complexity of the cardiac metabolic network, pharmacological and genetic tools have been engaged to manipulate cardiac metabolism in a variety of research models. In concert, a host of therapeutic interventions have been tested clinically to target substrate preference, insulin sensitivity, and mitochondrial function. In addition, the contribution of cellular metabolism to growth, survival, and other signaling pathways through the production of metabolic intermediates has been increasingly noted. In this review, we provide an overview of the cardiac metabolic network and highlight alterations observed in cardiac pathologies as well as strategies used as metabolic therapies in heart failure. Lastly, the ability of metabolic derivatives to intersect growth and survival are also discussed. (Circ Res. 2013;113:603-616.)

Key Words: cardiac metabolism ■ cardiac pathology ■ metabolic signaling ■ metabolic therapy

The mammalian heart must contract incessantly, thus, the requirement for energy to fuel optimal function is immense. Because the high-energy phosphate storage within the cardiomyocyte is minimal, only sufficient to sustain the heart beat for a few seconds, a tight coupling of ATP production and myocardial contraction is essential for normal cardiac function. Central to the coordinated energy transduction function is the multipurpose organelle mitochondrion that not only generates >95% of ATP used by the heart, but also regulates intracellular calcium homeostasis, signaling, and cell death. Although a constant supply of substrates through the metabolic network is paramount for mitochondrial conversion of ATP, it is increasingly recognized that metabolites generated by both ATP-producing and non–ATP-producing pathways can become critical regulators of cell function. Thus, the importance of substrate metabolism to cardiac pump function is beyond the scope of only modulation of energy supply. In this article, we provide an overview of changes in cardiac fuel metabolism under pathological conditions followed by recent progress on targeting cardiac metabolism for improving myocardial energetics and function. In addition, we summarize the emerging role of cardiac metabolism in governing myocardial growth and survival pathways.

Characteristics of Fuel Metabolism in the Heart

Capacity and Flexibility of Substrate Metabolism for ATP Production

The heart is capable of using all classes of energy substrates, including carbohydrates, lipids, amino acids, and ketone bodies, for ATP production in the mitochondrion (Figure 1, for details see reviews).1–3 Mitochondria occupy one third of the cell volume in cardiac myocytes, making them the cell type with the highest mitochondria content.4 The robustness of cardiac metabolism is reflected by its highest oxygen consumption rate on the per unit weight basis. For a human heart, the amount of ATP turned over during a 1-day period is 15 to 20 times of its own weight. In a normal heart, mitochondria are largely fueled by fatty acyl-coenzyme A (CoA) and pyruvate, which are the primary metabolites of fatty acids and carbohydrates, respectively. The entry of long-chain acyl-CoA into the mitochondrion is a regulated process, with the rate-limiting step at the carnitine-palmitoyltransferase-1 (CPT1) reaction. The oxidation of pyruvate is regulated at the pyruvate dehydrogenase (PDH) reaction. Other substrates, including lactate, ketone bodies, and amino acids, can enter mitochondria directly for oxidation. Metabolism of ketone bodies yields acetyl-CoA, whereas amino acid catabolism yields...
keto-acids, which are further metabolized to enter the tricarboxylic acid cycle. The contribution of ketone bodies and amino acids to overall cardiac oxidative metabolism is considered to be minor because of the low availability of these substrates under normal physiological conditions. 

It is widely accepted that fatty acids are the predominant substrate used in the adult myocardium. However, the cardiac metabolic network is highly flexible in using other substrates when they become abundantly available (Figure 1). For example, cardiac extraction and oxidation of lactate becomes predominant during exercise as skeletal muscle lactate production increases. Prolonged fasting or ketogenic diet increases the blood level of ketone bodies and results in enhanced use by the heart. In isolated perfused hearts, the addition of lactate or blood level of ketone bodies and results in enhanced use by well as allosteric regulation by substrates and their metabolites participating in several additional pathways that do not lend to ATP supply.

Apart from substrate availability, complex regulatory mechanisms contribute to metabolic flexibility at multiple levels, including transcriptional regulation and post-translational modification of key proteins involved in each metabolic pathway as well as allosteric regulation by substrates and their metabolites (Table 1). For example, transcriptional regulation of the proteins involved in fatty acid oxidation (FAO) by the peroxisome proliferator–activated receptor (PPAR/estrogen-related receptor-α) circuit is a major mechanism in the transition of the glycolysis-dependent fetal heart to oxidative metabolism in the adult heart. Likewise, transcriptional regulation by hypoxia-inducible factor-1α is responsible for the metabolic adaptation to hypoxic and ischemic conditions. Although transcriptional mechanisms contribute to the establishment of the network, post-translational modifications of key enzymes in the metabolic pathways regulate the fluxes. Phosphorylation and inactivation of PDH by PDH kinase 4 plays a key role in the shift of substrate oxidation between glucose and fatty acid in the heart. The phosphorylation of the branched-chain-α-ketoacid dehydrogenase (BCKD), regulated by BCKD kinase and a mitochondrial localized phosphatase (protein phosphatase 2Cm), governs the oxidation of branch amino acids.

### Intermediates of Glucose Metabolism

Although glucose catabolism through glycolysis primarily yields pyruvate for subsequent oxidation, glycolytic intermediates can participate in several additional pathways that do not lend to ATP generation. These pathways are of biological significance in the heart despite the small fluxes. Glucose 6-phosphate (G6P) produced by the hexokinase reaction enters the pentose phosphate pathway (PPP), yielding nicotinamide adenine dinucleotide phosphate (NADPH) during the oxidative phase and 5-carbon sugars in the subsequent nonoxidative phase. The supply of NADPH from the PPP is important for antioxidant defense because NADPH is required for maintaining the level of reduced glutathione. It has been shown that deficiency of G6P dehydrogenase (G6PD), the first and rate-limiting enzyme of the PPP, exacerbates ischemia–reperfusion injury in mice, indicating a protective role of the PPP against oxidative injury. End products of the nonoxidative phase of the PPP are also of significance because ribose 5-phosphate becomes a substrate for nucleotide or nucleic acid synthesis, whereas xylulose 5-phosphate has been suggested as a transcriptional signaling molecule.

An alternative fate of G6P is the production of sorbitol, via the enzyme aldose reductase (AR), in the polyol pathway. The role of the polyol pathway in normal cardiac metabolism is

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**Nonstandard Abbreviations and Acronyms**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
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<tbody>
<tr>
<td>PDH</td>
<td>pyruvate dehydrogenase</td>
</tr>
<tr>
<td>NADPH</td>
<td>nicotinamide adenine dinucleotide phosphate</td>
</tr>
<tr>
<td>G6P</td>
<td>glucose 6-phosphate</td>
</tr>
<tr>
<td>F6P</td>
<td>fructose 6-phosphate</td>
</tr>
<tr>
<td>ATP</td>
<td>adenosine triphosphate</td>
</tr>
<tr>
<td>ADP</td>
<td>adenosine diphosphate</td>
</tr>
<tr>
<td>PPARGamma</td>
<td>peroxisome proliferator-activated receptorgamma</td>
</tr>
<tr>
<td>PPARalpha</td>
<td>peroxisome proliferator-activated receptoralpha</td>
</tr>
<tr>
<td>mCPT1</td>
<td>muscle carnitine palmitoyltransferase 1</td>
</tr>
<tr>
<td>TCA</td>
<td>tricarboxylic acid cycle</td>
</tr>
<tr>
<td>Ox Phos</td>
<td>oxidative phosphorylation</td>
</tr>
<tr>
<td>TAG</td>
<td>triacylglycerol</td>
</tr>
<tr>
<td>Acyl CoAs</td>
<td>acyl-CoA</td>
</tr>
<tr>
<td>TAG</td>
<td>triacylglycerol</td>
</tr>
<tr>
<td>DGAT</td>
<td>diacylglycerol acyltransferase</td>
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<tr>
<td>ATGL</td>
<td>adipose triglyceride lipase</td>
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**Figure 1. Overview of the metabolic network.**

The energy-yielding substrates (fatty acids, glucose, ketones, and amino acids) converge on acetyl-CoA production with subsequent entry into the tricarboxylic acid (TCA) cycle. The final step of energy transfer is accomplished through oxidative phosphorylation (OxPhos), supplying >95% of ATP consumed by the heart. The boxes (in pink) above each metabolic pathway indicate the pathological and physiological condition in which the specific substrate becomes a predominant contributor to metabolism. ATGL indicates adipose triglyceride lipase; DGAT, diacylglycerol acyltransferase; mCPT1, muscle carnitine-palmitoyl transferase-1; PDH, pyruvate dehydrogenase; TAG, triacylglycerol; and TCA, tricarboxylic acid.
Table 1. Regulators of Substrate Metabolism

<table>
<thead>
<tr>
<th>Pathway</th>
<th>Stimulation</th>
<th>Inhibition</th>
</tr>
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<tbody>
<tr>
<td>Glycolysis</td>
<td>HIF1α132</td>
<td>ATP16</td>
</tr>
<tr>
<td></td>
<td>PPARγ12</td>
<td>NADH16</td>
</tr>
<tr>
<td></td>
<td>AMPK13</td>
<td>G6P14</td>
</tr>
<tr>
<td></td>
<td>Insulin14</td>
<td>citrate17</td>
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<tr>
<td></td>
<td>Epinephrine15</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AMP, ADP, Pi16</td>
<td></td>
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<tr>
<td></td>
<td>NAD14</td>
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<tr>
<td></td>
<td>F1, 6Bp16</td>
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<tr>
<td>Glucose oxidation</td>
<td>Insulin18</td>
<td>PPARγ12</td>
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<td></td>
<td>Epinephrine15</td>
<td>FOX120</td>
</tr>
<tr>
<td></td>
<td>NAD14</td>
<td>PDK423</td>
</tr>
<tr>
<td></td>
<td>Calcium19</td>
<td>Fatty acids7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Acetyl-CoA, NADH, ATP16</td>
</tr>
<tr>
<td>Fatty acid oxidation</td>
<td>PPAR/PGC-1α/ERRα/12,29-31</td>
<td>ACC225</td>
</tr>
<tr>
<td></td>
<td>FOX120</td>
<td>Malonyl-CoA26</td>
</tr>
<tr>
<td></td>
<td>AMPK13</td>
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</tr>
<tr>
<td></td>
<td>MCD17</td>
<td>Lactate11</td>
</tr>
<tr>
<td></td>
<td>Adiponectin22,23</td>
<td>Ketone bodies50</td>
</tr>
<tr>
<td></td>
<td>Fatty acids26</td>
<td></td>
</tr>
<tr>
<td>BCAA catabolism</td>
<td>PP2Cm26,28</td>
<td>BCKDK24</td>
</tr>
<tr>
<td></td>
<td>Glucagon27</td>
<td>NADH, CoA esters50</td>
</tr>
<tr>
<td>Ketone body oxidation</td>
<td>Acetate30</td>
<td></td>
</tr>
</tbody>
</table>

Known factors of transcription, protein modification, and allosteric regulation involved in the stimulation or inhibition of metabolic pathways. ACC2 indicates acetyl-CoA carboxylase 2; AMPK, AMP-activated protein kinase; BCKDK, branched chain ketoacid dehydrogenase kinase; ERRα, estrogen-related receptor-α; F1,6Bp, fructose 1,6-biphosphate; FOXO1, forkhead box protein O1; G6P, glucose 6-phosphate; HIF1α, hypoxia-inducible factor-1α; MCD, malonyl-CoA decarboxylase; NAD+, nicotinamide adenine dinucleotide; NADH, nicotinamide adenine dinucleotide, reduced; PDK4, pyruvate dehydrogenase kinase 4; PGC-1α, peroxisome proliferator–activated receptor-γ coactivator-1α; Pi, inorganic phosphate; PP2Cm, protein phosphatase 2Cm; and PPARγ, peroxisome proliferator–activated receptor-γ.

unknown. However, increased flux has been noted in patients with diabetes mellitus and has been associated with abnormal glucose metabolism and cardiac dysfunction. Increased AR flux has also been implicated in the myocardial response to ischemia–reperfusion injury. Elucidation of the role of the polypeptide pathway in mouse models should be used with caution as both expression and activity of AR are significantly lower in mice than in humans; however, the use of transgenic mice overexpressing human AR could be translatable.

The glycolytic intermediate fructose 6-phosphate can diverge into the hexosamine biosynthetic pathway yielding uridine diphosphate-N-acetylglucosamine, via the enzyme glutamine fructose 6-phosphate amidotransferase. Uridine diphosphate-N-acetylglucosamine is used as the substrate for O-linked–GlcNAc transferase, which catalyzes the O-GlcNAcylation of proteins. Increases in protein O-linked GlcNAcation have been observed in diabetes mellitus and proposed to be responsible for altered insulin sensitivity and FAO. Recent studies show that protein O-linked GlcNAcation is enhanced during ischemia–reperfusion and represents a cardioprotective mechanism against injury.

Turnover of Endogenous Substrates
The heart stores fuel in the form of glycogen and triacylglycerol (TAG; Figure 1). The turnover rate of the cardiac glycogen pool is rather low under normal conditions in the adult heart. Glycogen metabolism has an essential role in the fetal heart because the absence of glycogen attributable to the deletion of glycogen synthase causes abnormal cardiac development. Glucose derived from glycogenolysis also provides a critical energy supply for cell survival during ischemia. Glycogen is also a key energy source to support metabolism during acute increases in cardiac workload.

The turnover of cardiac TAG is more robust compared with the glycogen pool although its functional role has been less understood until recently. It has been postulated that fatty acids derived from the myocardial TAG pool can be oxidized and contribute ~10% to the total ATP production under normal physiological conditions. A significant loss of TAG turnover was observed in hearts from failing rats, whereas accelerated turnover was noted in diabetic rats. These results suggest that the intracellular TAG pool is a dynamic entity, but the functional significance of altered TAG turnover under pathological conditions is poorly understood.

Recent studies suggest that the turnover of TAG pool is an important regulatory mechanism of fatty acid metabolism in the myocardium. Genetic manipulation of diacylglycerol acyltransferase (DGAT), the final enzyme in the synthesis of TAG from diacylglycerol, or adipose triglyceride lipase, the enzyme responsible for TAG hydrolysis, leads to significant changes of fatty acid uptake and oxidation in the mouse heart. Although deletion of DGAT1, the major isoform of DGAT in the heart, did not significantly decrease total cardiac TAG content, it was associated with decreased FAO and increased glucose uptake. Conversely, DGAT1 overexpression resulted in a 2-fold increase in cardiac TAG with both increased uptake and oxidation of exogenous fatty acids. Global deletion of adipose triglyceride lipase resulted in massive lipid accumulation and severe cardiomyopathy associated with decreased FAO. However, cardiac-specific overexpression of adipose triglyceride lipase also led to decreased rates of FAO with increased rates of glucose oxidation, suggesting a nonlinear relationship between TAG turnover and FAO.

Modulation of Contractile Function by Cardiac Metabolism Under Pathological Conditions

Pathological Hypertrophy and Failure
It is well established that cardiac metabolism undergoes a reprogramming in response to pathological hypertrophy, characterized by increased reliance on glucose metabolism and decreased FAO (Figures 2 and 3). Increased glucose use in the hypertrophied heart is predominantly characterized as an upregulation of glucose uptake and glycolysis, with either no change or a decrease in glucose oxidation. These changes, combined with decreases in overall FAO, likely represent reduced capacity for mitochondrial oxidative metabolism. In small animal models, the shift in substrate preference is associated with downregulation of the transcriptional mechanisms for FAO and mitochondrial biogenesis mediated via PPARα and PGC1α. Because these changes resemble a reversal of metabolic maturation during the transition from a fetal to adult heart, many have considered the metabolic...
changes in hypertrophied and failing hearts as a reappearance of the fetal metabolic profile.

Is there any advantage of switching to a fetal-like metabolism in the hypertrophied and failing myocardium? A shift from FAO to glucose use improves oxygen efficiency for ATP synthesis and is thus considered beneficial.75,76 This becomes particularly important for heart failure caused by chronic ischemic cardiomyopathy where oxygen supply is limited. There have been concerns whether increased glucose uptake and use in adult heart impairs cardiac function because cardiomyocytes cultured in high glucose media develop so called glucotoxicity.77–80 Transgenic mice with cardiac-specific overexpression of insulin-independent glucose transporter (GLUT1) showed substantial increases of glucose uptake and glycolysis but maintained normal cardiac function and lifespan, suggesting that increased glucose use does not harm the adult heart in the long term.81 A key question remaining is whether metabolic remodeling is adaptive or maladaptive to the high energy demand in the hypertrophied and failing heart. It is known that pathological cardiac hypertrophy is associated with depletion of energy reserves manifested as maintained ATP levels but a reduction of the energy reserve compound, phosphocreatine (PCr).82,83 This is reflected as a decreased PCr/ATP ratio and eventually, as compensated hypertrophy advances to overt heart failure, significant decreases of ATP are observed.84,85 The PCr/ATP ratio has been shown to be a superior predictor of mortality as compared with ejection fraction (EF) in patients with heart failure,86 which is in agreement with the long-standing hypothesis that energy starvation contributes to the pathogenesis and progression of heart failure (see reviews).84,85,87 These observations suggest that the fetal-like metabolic profile in cardiac hypertrophy is maladaptive for sustaining myocardial energetics and function (Figure 3).

Animal studies have shown that metabolic remodeling in hypertrophied heart is associated with decreases in the overall ATP synthesis by oxidative metabolism.87 Although glycolysis is increased, its contribution to total ATP synthesis is limited as glycolytic ATP accounts for <5% of total energy used by the heart.87 Furthermore, glucose entry in the adult heart is controlled by insulin; the coexisting insulin resistance in heart failure would limit the glucose availability and hence compromise the capacity for ATP synthesis.88,89 A proof-of-concept study shows that increasing glucose uptake capacity in mouse heart via an insulin-independent mechanism delays the transition of cardiac hypertrophy to failure.90 Other studies show
that cardiac energetics and function can also be preserved in rodent models of heart failure by sustaining FAO or by enhancing ATP synthesis and transfer via the creatine kinase reaction.91–93 Therefore, the ATP synthesis capacity seems to be more important than the substrate selection for sustaining cardiac energetics and function in these models.

In addition to glycolysis and pyruvate oxidation, multiple accessory pathways of glucose metabolism (Figure 2) have also been altered in the hypertrophied myocardium. Increased flux of the anaplerotic pathway, primarily via increased malic enzyme, has been reported in hypertrophied rodent heart.95–96 Such a change is considered maladaptive because it short-circuits pyruvate into the second half of the tricarboxylic acid cycle and hence produces less nicotinamide adenine dinucleotide for oxidative phosphorylation. The regulatory enzyme of the PPP, G6PD, was upregulated in the hearts of animals subjected to pressure-overload.96,97 Increased activity of G6PD in heart would result in the increased production of NADPH and impaired the redox regulation. It is also proposed that increased glucose use augments hexosamine biosynthetic pathway flux, resulting in enhanced O-GlcNAcylation.98 Increased glucose metabolism also elevates the citrate level in the cytosol, providing more acetyl-CoA for the acetylation of proteins.99 It remains to be determined whether these changes contribute to the maladaptive nature of increased glucose use in heart failure. These pathways have been less investigated because their fluxes are small and they do not contribute to the once ultimate goal of cardiac metabolism, ATP production. However, given the emerging significance of non–ATP-producing pathways in cardiac biology, this paradigm is rapidly changing. We shall expect a wealth of information relating to this in the future.

Metabolic Cardiomyopathy Associated With Obesity and Diabetes Mellitus

In obese or individuals with diabetes mellitus, cardiac dysfunction observed independent of macro- and microvascular disease is considered a consequence of diabetic cardiomyopathy. Increased fatty acid uptake and oxidation associated with reduced glucose oxidation have been observed in both animal models and patients of type 2 diabetes mellitus.102–104 Cardiac dysfunction in obesity and diabetes mellitus has been associated with increased myocardial oxygen consumption, reduced cardiac efficiency, and increased oxidative stress, suggesting that increased rates of FAO are detrimental to cardiac function (Figure 3).102,105,106 As discussed above, one mechanism for the undesirable effect of high FAO is the lower \( \text{O}_2 \) efficiency,75,76 as well as the increased presence of fatty acid derivatives that may further reduce the efficiency by uncoupling the mitochondria.105 In skeletal muscle, increased influx of fatty acid to mitochondria was associated with incomplete oxidation and development of insulin resistance.106 However, this was not observed in the mouse heart during high-fat feeding107 or with increased import of long-chain fatty acids to the mitochondria attributable to deletion of acetyl-CoA carboxylase 2.93

A unique aspect of cardiac metabolism in obesity and diabetes mellitus is that the supply of substrates exceeds the need for ATP synthesis. Despite increased FAO, hearts of obese individuals and those with diabetes mellitus accumulate a significant amount of lipid (Figure 3). A positive correlation of cardiac lipid accumulation and cardiac dysfunction has been shown giving rise to the term lipotoxic cardiomyopathy.110–112 Additional studies show that increases of lipid supply in animal models of cardiac lipotoxicity exceed the increases in the rate of oxidation, which eventually leads to downregulation of FAO, accumulation of toxic lipid intermediates, and contractile failure.112,113 Genetic manipulations in mice that reduce fatty acid uptake or increase the storage capacity of neutral lipids in the heart rescue the lipotoxic phenotype.62,114,115 These results suggest that the metabolic derangements in lipotoxic cardiomyopathy are rooted in the inappropriate matching of lipid supply and oxidation rather than a simple increase of FAO. The molecular mediator(s) of the cardiomyopathy in this case is largely elusive and likely multifactorial in nature. Although the accumulation of neutral lipids correlates closely with functional phenotype, whether it is the cause or a mere reporter of lipotoxicity is not clear. Increases in intramuscular lipid are not always associated with detrimental effects. Both animals and humans increase triglyceride content in the heart and skeletal muscle in response to exercise training, which is associated with improved function.62,116,117

Although glucose uptake and use for ATP synthesis is reduced, attributable to insulin resistance and increased FAO, increased flux of the accessory pathways of glucose metabolism has been identified in the diabetic myocardium. In the polyl pathway, increased AR gene expression was observed, whereas AR inhibition improved cardiac function in patients with diabetes mellitus.42 In models of diabetic cardiomyopathy, elevated levels of uridine diphosphate-N-acetylgalcosamine, O-GlcNAc, and O-linked–GlcNAc transferase were associated with impaired excitation contraction coupling, suggesting a role of increased hexosamine biosynthetic pathway flux in diabetic cardiac dysfunction.80,118,119 Consistent with these observations, increased expression of O-GlcNAcase, the antagonist of O-linked–GlcNAc transferase, improved cardiac function in diabetic mice.120

Metabolic Therapies for Heart Failure

Targeting Substrate Preference

The shift of substrate preference to glucose in pathological hypertrophy was considered adaptive based on the theoretical higher oxygen efficiency of ATP synthesis from glucose.121 Therefore, various metabolic therapies focusing on the promotion of glucose oxidation have been used (Table 2). One strategic target has been CPT1, the enzyme that is the gateway for long-chain fatty acid uptake into the mitochondria. The muscle form of the CPT1 inhibitors, such as etomoxir, perhexiline, and oxefenicine, have been associated with reduced cardiac FAO and elevated glucose oxidation in both animal models and humans. Etomoxir has been shown to increase expression and activity of the sarcoendoplasmic reticulum calcium ATPase.122,123 Long-term treatment with etomoxir in pressure overloaded hearts improved functional capacity and myocardial performance.124 The first human clinical trial evaluating
Table 2. Metabolic Therapies Used in the Treatment of Heart Failure

<table>
<thead>
<tr>
<th>Substrate preference</th>
<th>mCPT1 inhibitors</th>
<th>Partial β-oxidation inhibitors</th>
<th>PDK inhibitors</th>
<th>MCD inhibitors</th>
<th>Nicotinic acid derivatives*</th>
<th>PPAR agonists</th>
<th>Insulin sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucagon-like peptides (GLP-1)</td>
<td>Metformin</td>
<td>Thiazolidinediones*</td>
<td>Mitochondrial function</td>
<td>PDE inhibitors</td>
<td>AMPK activators</td>
<td>MitoQ</td>
<td>MitoTEMPO</td>
</tr>
</tbody>
</table>

AMPK indicates AMP-activated protein kinase; EUK-8, superoxide dismutase and catalase mimetic; MCD, malonyl CoA decarboxylase; mCPT1, muscle form of carnitine-palmitoyl transferase-1; MitoQ, mitochondrial-targeted antioxidant; MitoTEMPO, mitochondria-targeted antioxidant with superoxide and alkyl radical scavenging properties; PDE, phosphodiesterase; PDK, pyruvate dehydrogenase kinase; PPAR, peroxisome proliferator-activated receptor; PUFAs, polyunsaturated fatty acids; and SS peptide, Szeto–Schiller peptide.

*Therapies with reported adverse effects.

eutomoxir in patients with chronic heart failure showed improved stroke volume and EF.125 A clinical trial evaluated the effect of perhexiline in patients with heart failure and observed improved Vo2 max, EF, and tolerance to dobutamine stress.126 In hypertrophic cardiomyopathy, perhexiline, in conjunction with medical management, increased the PCr/ATP ratio, corrected energy-dependent LV diastolic relaxation, increased Vo2, and improved the quality of life.127 Although not available for human use, oxefunicin treatment in pacing-induced heart failure in dogs, when provided early, slowed the development of heart failure and prevented LV chamber dilation and LV wall thinning compared with placebo.128

Dichloroacetate (DCA) increases PDH activity by inhibiting pyruvate kinase dehydrogenase (PDK) and as a consequence promotes glucose oxidation. The efficacy of DCA treatment in functional recovery during reperfusion has been shown in multiple animal models.129–132 DCA also improves cardiac function in right ventricular hypertrophy and failure.133,134 In a recent study examining hyperthyroidism and cardiac hypertrophy in rats, DCA administration completely reversed reductions in PDH flux and significantly reduced cardiac hypertrophy without affecting cardiac output.135 Although human data are limited because of the chronic neurotoxicity of DCA,136–138 a study in patients with angina and coronary artery disease revealed that infusion of DCA during left heart catheterization was associated with increased stroke volume and myocardial efficiency index (LV work/myocardial oxygen consumption).139

Malonyl CoA decarboxylase is a key regulator of malonyl CoA degradation and, thus, its activity relieves the inhibition of fatty acid entry into the mitochondria. Pharmacological inhibition or cardiac-specific deletion of malonyl CoA decarboxylase has been shown to limit FAO, increase glucose oxidation, and improve cardiac function after ischemia/reperfusion injury in both rodent140,141 and porcine models.142 Although clearly effective in treatment of cardiac ischemia, it has not been shown whether targeted inhibition of malonyl CoA decarboxylase in heart failure is likewise protective.

Although enhancing glucose use seems to be beneficial for the failing heart, decreasing fatty acid supply to hypertrophied and failing hearts seems to be detrimental. Acipimox is a nicotinic acid derivative that acutely inhibits lipolysis in adipose tissue and hence decreases plasma free fatty acids level. When administered to patients with idiopathic dilated cardiomyopathy, myocardial free fatty acids uptake was reduced by >80% with enhanced glucose uptake. Unfortunately, cardiac work and efficiency declined after acipimox treatment.143 In long-term treatment of patients with heart failure with acipimox, increases in whole-body glucose use and decreased lipid use rates were noted, but myocardial function, exercise capacity, and cardiac index scores remained unaffected.144 These studies suggest that promoting glucose use via restriction of fatty acid delivery to the myocardium is not an ideal strategy for enhancement of cardiac function via the optimization of cardiac metabolism.

Because oxidation of fatty acids is the predominant and critical energy source for cardiac function, promotion of cardiac FAO would seem to be desirable for long-term treatment. Targeting PPARα, the major regulator of cardiac lipid metabolism, however, has yielded mixed outcomes. Overall, in various animal models of cardiac hypertrophy and heart failure, PPARα agonism maintained expression of genes involved in FAO with significantly improved,145,146 relatively modest,147,148 or no benefit on cardiac function.49 Furthermore, PPARα agonism has been shown to exacerbate posts ischemic injury.149,150

Activation of PPARα-mediated transcription has broad effects on lipid metabolism, including lipid uptake. Excessive fatty acid uptake relative to the oxidation would contribute to lipotoxicity.114 Concerning this, direct activation of FAO at the level of the mitochondria may provide a more effective therapeutic strategy for sustaining myocardial energetics. Although no drug is available for clinical studies, several proof-of-concept studies have been performed in mice. Overexpression of PDK4 in mice promoted cardiac FAO at the expense of glucose but had no effect on cardiac function either under normal or ischemic conditions.151 However, introduction of the PDK4 transgene into mice expressing a constitutively active form of the phosphatase calcineurin failed to rescue cardiac dysfunction and led to an increase in mortality.152 On the contrary, deletion of acetyl-CoA carboxylase 2 increased myocardial FAO in normal mice and prevented the switch to increased glucose reliance during pressure-overload–induced hypertrophy.93 Cardiac function
and myocardial energetics were also sustained, suggesting a benefit of maintaining FAO during pathological hypertrophy. Several recent studies have also demonstrated the effectiveness of high-fat diets in protection against the development of heart failure in animal models. \cite{91,153,154}

Taken together, the evidence thus far suggests that enhancing glucose use in the hypertrophied and failing heart improves cardiac function and symptoms of heart failure in the short term. Clinical application of metabolic therapy of this kind depends on the ultimate test of its impact on the long-term mortality. However, strategies of enhancing glucose use by removing the contribution of fatty acids seem to be less promising. Moreover, recent preclinical studies suggest that sustaining FAO in the hypertrophied heart may be suitable for the preservation of myocardial energetics and function. \cite{90,93,154}

**Targeting Insulin Sensitivity**

Insulin resistance has been shown to precede and predict the development of heart failure, independent of established diabetes mellitus. \cite{355} Moreover, insulin resistance is positively correlated with New York Heart Association functional class. \cite{156} Because glucose uptake in the adult heart is largely controlled by insulin-sensitive mechanisms, insulin resistance would be an obstacle for measures that seek to enhance myocardial glucose use. Although not directly tested, insulin-sensitizing agents have been used in patients with heart failure with metabolic disturbances (Table 2) and have yielded auspicious results.

Thiazolidinediones, PPARγ agonists including rosiglitazone and pioglitazone, are used as oral hypoglycemic and insulin-sensitizing agents. Thiazolidinediones successfully enhance glucose uptake and oxidation, especially in diabetic animal models, and improve functional recovery after ischemia. \cite{157,158} However, 1 study showed that rosiglitazone increased mortality post-myocardial infarction in rats without alterations in LV remodeling. \cite{159} Similarly, rosiglitazone was associated with a higher risk of cardiovascular events, including congestive heart failure in the A Diabetes Outcome Progression Trial (ADOPT) trial, as compared with cohorts treated with glyburide or metformin. \cite{160} In the Prospective Pioglitazone Clinical Trial (PROACTIVE) trial, pioglitazone decreased all-cause mortality, nonfatal MI, and stroke but significantly increased rates of symptomatic edema and congestive heart failure in patients with diabetes mellitus and cardiovascular disease. \cite{161}

Another widely used insulin-sensitizing drug is metformin that is often used as first-line therapy for individuals with diabetes mellitus. Metformin acts as an AMP-activated protein kinase activator in the liver and has been shown to increase glucose uptake both in basal and insulin-stimulated conditions in insulin-resistant cardiomyocytes. \cite{163} Of note, activation of AMPK by metformin in human heart has not been reported. In animal studies, metformin improved LV function and remodeling, whereas it reduced myocardial lipid accumulation and fibrosis. \cite{164,165} Masoudi et al. \cite{166} performed a retrospective cohort analysis on subjects with congestive heart failure and diabetes mellitus and found that metformin use for 1 year was associated with a 13% lower mortality compared with sulfonylurea or insulin therapy. Although these results are promising, randomized prospective trials are still needed to evaluate the potential clinical benefits of metformin in patients with heart failure and without diabetes mellitus.

Glucagon-like peptide-1 (GLP-1) is secreted by intestinal cells in response to the presence of nutrients. Once in the circulation, it stimulates insulin secretion, enhances insulin sensitivity, and promotes glucose use in the myocardium. In a canine model of pacing-induced dilated cardiomyopathy, GLP-1 treatment increased myocardial glucose uptake and was associated with decreased LV end-diastolic pressure, increased stroke volume, and increased cardiac output. \cite{167} In patients with heart failure, GLP-1, in addition to standard medical therapy, led to improvements in EF and maximal aerobic capacity compared with controls who received standard medical therapy alone. \cite{168} A study examining patients with an acute myocardial infarction and EF<40% after successful angioplasty treated with 72 hours of GLP-1 infusion demonstrated significantly greater EF associated with improved global and regional wall motion score indices compared with controls. \cite{169}

**Targeting Mitochondrial Function**

It is well known that heart failure is associated with mitochondrial dysfunction but therapies specifically targeted to improving mitochondrial function are rather limited. The nitric oxide pathway is a potential stimulator of mitochondrial biogenesis. \cite{170} Modulation of this pathway with phosphodiesterase 5 inhibitors was related to increased mitochondrial biogenesis. \cite{171} Treatment with the phosphodiesterase 5 inhibitors, sildenafil, improved cardiac index and right ventricular EF in patients with heart failure, \cite{172} but additional studies are required to determine whether the benefit can be attributed to increased mitochondrial biogenesis and function.

Mitochondrial dysfunction in heart failure is associated with increased oxidative stress, making mitochondria-targeted reactive oxygen species scavenging an attractive therapeutic strategy. Several antioxidants that accumulate in the mitochondrial matrix have demonstrated cardioprotective effects in animal models. Mitoquinone improved functional recovery from ischemia in the isolated rat heart \cite{173} as well as prevented doxorubicin-induced cardiac dysfunction, fibrosis, and apoptosis. \cite{174} MitoTEMPO, a superoxide and alkyl scavenger, demonstrated cardioprotective effects in hypertension and diabetes mellitus models. \cite{175,176} EUK-8, a superoxide dismutase and catalase mimetic, rescued cardiac dysfunction in genetic models of increased oxidative stress. \cite{177,178} Finally, Szeto–Schiller peptides have shown cardiac protection in guinea pig hearts subjected to ischemia–reperfusion injury and mouse models of hypertrophy and failure, in part, by reducing oxidative stress. \cite{179,180} So far, clinical studies using such a strategy are rather limited. However, a Phase IIa clinical trial on the safety and efficacy of the Szeto–Schiller peptide, Bendavia, on reperfusion injury is ongoing. \cite{181}

Although mitochondria-specific antioxidants have shown promising results for the treatment of heart failure, general antioxidants in clinical trials have not. Vitamin E, also known as α-tocopherol, has been extensively studied in heart failure. Large clinical trials revealed that vitamin E can actually increase the risk of developing heart failure after myocardial infarction. \cite{182} The Heart Outcomes Prevention Evaluation (HOPE) and HOPE- the Ongoing Outcomes (HOPE-TOO) trials also suggested that long-term vitamin E supplementation increases...
the risk of heart failure and heart failure exacerbations with no improvement in other cardiovascular outcomes.\textsuperscript{183} Further work is needed to elucidate the differences between mitochondria-specific and general antioxidant therapy for heart failure.

**Dietary Strategies**

The benefits of polyunsaturated fatty acids in decreasing the incidence of coronary artery disease and sudden cardiac death are well accepted. Polyunsaturated fatty acids also improve various factors related to heart failure including lipid metabolism, mitochondrial function, endothelial function, and inflammation. Clinical evidence now suggests that polyunsaturated fatty acids can prevent the development or progression of heart failure. A 12-year study following >4700 adults found an inverse correlation between incidence of heart failure and dietary consumption of tuna and other fish, with the highest intake of dietary long-chain n-3 fatty acid offering a 37% lower risk of heart failure.\textsuperscript{184} A randomized double-blind, placebo controlled trial (Gruppo Italiano per lo Studio della Sopravvivenza nell’Infarto Miocardico-Heart Failure, GISSI-HF) showed that patients with heart failure treated with low-dose eicosapentaenoic acid and docosahexaenoic acid for a median time of 3.9 years had a significantly lower mortality rate and decreased hospital admissions for cardiovascular causes.\textsuperscript{185} A recent meta-analysis involving 7 trials found that fish oil supplementation in nonischaemic heart failure significantly increased LVEF.\textsuperscript{186} In contrary, high levels of long-chain monounsaturated fatty acids were associated with a greater incidence of congestive heart failure, suggesting potential cardiac toxicity of this lipid species.\textsuperscript{187}

**Metabolic Modulation of Growth and Survival Pathways**

The effects of metabolism on growth, proliferation, and survival pathways have been increasingly recognized in recent years, especially in cancer biology. Although a large fraction of the metabolic fluxes in the heart is devoted to oxidative metabolism for ATP synthesis, substrate metabolism has significant impact on multiple aspects of cardiac biology. Closely related to the topic of cardiac hypertrophy and failure discussed above, here we present the recent development on the role of metabolism in the regulation of cardiomyocyte growth, survival, and autophagy (Figure 4).

**Regulation of Mammalian Target of Rapamycin Signaling**

Recently, an interesting finding on the influence of fatty acids on cardiac myocyte growth was made in Burmese pythons.\textsuperscript{188} Elevations in 3 fatty acids (palmitic acid, myristic acid, and palmitoleic acid) were identified as inducers of reversible cardiac hypertrophy during the feeding period and were associated with increased mammalian target of rapamycin (mTOR) phosphorylation. This effect of fatty acids on mTOR has been previously shown in skeletal muscle and liver tissue of rats fed a high-fat diet.\textsuperscript{189,190} In addition, incubation of myotubes with palmitate increased phosphorylation of S6 kinase, a downstream target of mTOR.\textsuperscript{190} Transgenic mouse models of enhanced lipid metabolism are generally associated with cardiac hypertrophy,\textsuperscript{191,192} but whether the increased uptake of fatty acids contribute to cardiac growth via the mTOR pathway has not been determined.

It has been shown that glucose phosphorylation is required for insulin-dependent activation of mTOR in the heart.\textsuperscript{193} A recent study suggested that accumulation of G6P during mechanical overload activated mTOR and caused contractile dysfunction by triggering endoplasmic reticulum stress stress.\textsuperscript{194} Because glucose metabolism is increased in the hypertrophied and failing heart, it is tempting to hypothesize that altered glucose metabolism is causally linked to the development of hypertrophy and dysfunction.

The effects of amino acids on protein synthesis have been well studied in cultured cells, animal models, and humans.\textsuperscript{195–200} Although the exact mechanisms are not known, the presence of amino acids has been shown to activate the mTOR complex and its downstream effectors.\textsuperscript{197,199} It has been suggested that amino acids activate mTOR through a calcium-dependent mechanism involving class III PI3K, or hVps34, which would combine the interaction of protein synthesis with inhibition of autophagy.\textsuperscript{196} Previous work demonstrated that mTOR and its downstream targets are affected by the availability of intracellular amino acids.\textsuperscript{201} Additional studies have specifically implicated the branched-chain amino acid, leucine, in the stimulation of the mTOR pathway.\textsuperscript{195,196,202,203} This has been particularly important in accounting for increased skeletal muscle protein synthesis during the postexercise recovery period\textsuperscript{200,204} and in atrophy associated with aging.\textsuperscript{205,206}

The above evidence offers strong support to the notion that mTOR behaves as a nutrient sensor. It remains to be determined whether one or multiple metabolites of the aforementioned substrates have a direct binding affinity for the mTOR complex. It is also not known whether different metabolic pathways affect mTOR signaling through distinct mechanisms or via a unifying effector.

**Apoptosis and Autophagy**

Ceramides, a sphingolipid composed of sphingosine and a fatty acid, have been purported to function as a signal that triggers apoptosis in lipotoxic cardiomyopathy.\textsuperscript{207} Elevated ceramide levels were found in the hearts of mice overexpressing enzymes of lipid metabolism, including acyl-CoA synthetase,\textsuperscript{62,113} lipoprotein lipase (LPL),\textsuperscript{191} and PPARγ,\textsuperscript{197} which was associated with

![Figure 4. Metabolic modulation of growth and survival pathways. Interactions of lipids, amino acids, and glucose metabolism with pathways of hypertrophy, autophagy, and apoptosis as represented in the literature from various cell culture and animal models. BCAAs indicates branched-chain amino acids; G6P, glucose 6-phosphate; mTOR, mammalian target of rapamycin; SFAs, saturated fatty acids; and UFAs, unsaturated fatty acids.](http://circres.ahajournals.org/)}
increased apoptosis and cardiac dysfunction. However, high-fat feeding in rodent models has not consistently recapitulated this observation. Although the content of cardiac ceramides was increased in rats fed a high-fat diet, no evidence of apoptosis or cardiac dysfunction was found. In addition, 10 or 12 weeks of a high-fat diet fed to mice failed to increase ceramide levels significantly. Ceramides were elevated in rat hearts subjected to coronary artery ligation, but provision of a high-fat diet during that interval did not further increase ceramide content.

In studies using cultured cells or neonatal rat ventricular myocytes, addition of palmitate to the media significantly increased measures of apoptosis. Similar findings were observed with addition of stearate, suggesting long-chain saturated fatty acids as the culprit. Interestingly, coinubation with the unsaturated fatty acid, oleate, significantly reduced apoptosis measures in cells. Because the metabolic rate of quiescent cells is vastly different from that of the beating heart, the observation could be confounded by the low oxidation rate of fatty acids in cell culture. However, cells exposed to different species of fatty acids showed differential outcomes, suggesting that the chain length and the degree of saturation influence the survival of cardiomyocytes under conditions of lipid overload. In rodents fed a high-fat diet, a lower ceramide content and reduced apoptotic events were observed in cardiomyocytes from the group receiving predominantly saturated fat, myristic acid, which increased the presence of ceramide accumulation into the TAG pool, and that provision of unsaturated fats in conjunction with saturated fats could promote survival by attenuation of apoptosis.

Recent work in mice demonstrated that a high milk-fat-based diet resulted in elevated supply of the 14 carbon (C14) saturated fat, myristic acid, which increased the presence of C14-ceramide, and was associated with cardiac hypertrophy, dysfunction, and increased autophagy. However, other studies using high-fat feeding models in mice have suggested that autophagy is impaired during the lipid overload condition. Furthermore, hearts from a porcine model exposed to a high-fat or atherogenic diet revealed progressive decreases in autophagy combined with increases in apoptosis. Whether metabolic derangement in the heart causes cardiac injury via inhibition of autophagy is an open question. Autophagy is critical for protein quality control, cellular homeostasis, and survival. However, increased autophagy can be adaptive or maladaptive to cardiac pathologies depending on the circumstances (see recent reviews). Although autophagy is known as an evolutionarily conserved response to metabolic stress, the metabolic mediators of autophagy are poorly understood at the molecular level. An expanded knowledge of the metabolic control of autophagy will facilitate targeting autophagy for therapeutics.

In summary, the knowledge on cardiac metabolism and its role in human diseases has increased explosively in recent years. Multidisciplinary approaches in both experimental and clinical research seem to converge on the concept that the capacity and flexibility of the metabolic network is essential for cardiac function. Although energy transfer is a primary function of cardiac metabolism, the sophistication of the system is being appreciated for its regulatory role through the interactions of the ATP-producing and non-ATP-producing pathways. Future advances of the field will elucidate novel disease mechanisms and identify new targets for metabolic therapy.

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changes in availability of eIF4E and phosphorylation of ribosomal protein S6 to mTOR signaling and ER stress in mammalian heart.


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