Etomoxir, a Carnitine Palmitoyltransferase I Inhibitor, Protects Hearts From Fatty Acid-Induced Ischemic Injury Independent of Changes in Long Chain Acylcarnitine

Gary D. Lopaschuk, Stephen R. Wall, Peter M. Olley, and Norman J. Davies

Fatty acids are known to increase the severity of injury during acute myocardial ischemia. In this study, we determined the effects of a carnitine palmitoyltransferase I inhibitor, ethyl 2-[6-(4-chlorophenoxy)hexyl]oxirane-2-carboxylate (Etomoxir) on reperfusion recovery of fatty acid perfused hearts. Following a 25-minute period of global ischemia, isolated working hearts reprefused with 1.2 mM palmitate, 11 mM glucose exhibited depressed function compared to hearts perfused with 11 mM glucose alone. A low dose of Etomoxir (10⁻⁹ M) decreased long chain acylcarnitine and long chain acyl-coenzyme A (CoA) levels but did not prevent depressed function. In contrast, a high dose of Etomoxir (10⁻⁶ M) prevented the palmitate-induced depression of function but did not decrease myocardial long chain acylcarnitine or long chain acyl-CoA levels. At this high dose of Etomoxir, oxygen consumption per unit work was decreased during reperfusion recovery, and ATP and creatine-phosphate levels were significantly higher after reperfusion. In aerobic hearts not subjected to ischemia, Etomoxir (10⁻⁶ M) increased glucose oxidation both in the presence and absence of palmitate, while 10⁻⁹ M Etomoxir had no effect. In these aerobic hearts, only the low dose of Etomoxir decreased long chain acylcarnitine and long chain acyl-CoA levels. These data demonstrate that Etomoxir (10⁻⁶ M) increases functional recovery of fatty acid perfused ischemic hearts. This protection is unrelated to changes in levels of long chain acylcarnitines but may be due to increased glucose use by the reperfused heart, resulting in decreased oxygen consumption per unit work. (Circulation Research 1988;63:1036-1043)

In the early hours following acute myocardial infarction, plasma free fatty acid content is elevated¹-³ and is thought to contribute to both myocardial infarct size and mortality.⁴-⁶ Fatty acid potentiation of ischemic injury occurs in several experimental models, including the in situ pig and dog heart⁷,⁸ as well as the isolated perfused rat heart.⁹ The detrimental effects of fatty acids have been attributed to an increased requirement of oxygen for catabolism or to the accumulation of potentially toxic intracellular intermediates of fatty acid metabolism. Two of these intermediates that accumulate in the ischemic myocardium are long chain acyl-coenzyme A (CoA) and long chain acylcarnitine.¹⁰ A host of studies in membrane vesicle and solubilized enzymes have demonstrated that these amphiphiles can alter the function of a number of critical membrane proteins.¹¹-¹⁵ In intact tissue, a correlation between acylcarnitine levels and the degree of ischemic injury has been suggested.⁷,¹⁶ although this finding has not been consistent.¹⁷ We recently demonstrated in isolated working rat hearts that fatty acids adversely affect functional recovery after ischemia (G.D. Lopaschuk and M. Spafford, submitted manuscript). Decreased recovery of fatty acid perfused hearts was accompanied by a large increase in myocardial long chain acylcarnitine levels, although it could not be determined if this increase caused the depression of functional recovery.

Recently, studies have appeared which demonstrate that agents which block fatty acid oxidation can protect the ischemic myocardium. Carnitine palmitoyltransferase I (CPT 1) inhibitors, such as POCA (sodium 2-[5-(4-chlorophenyl)-pentyl]oxirane-2-carboxylate), TDGA (2-tetraglycidic acid), and...
oxefencine appear to protect the ischemic myocardium, perhaps due to a decrease in myocardial long chain acylcarnitine levels. However, a switch from predominantly fatty acid oxidation to carbohydrate oxidation, with a resultant decrease in myocardial oxygen consumption, could also explain the salutary effects of this drug.

Etomoxir (ethyl 2-[6-(4-chlorophenoxy)hexyl]oxirane-2-carboxylate) is a new CPT 1 inhibitor that is a more potent analogue of POCA. Etomoxir is of potential interest in the treatment of diabetes since inhibition of fatty acid oxidation should increase glucose utilization and decrease gluconeogenesis. By inhibiting fatty acid oxidation, fatty acid-induced inhibition of glycolysis may be overcome, thereby increasing glucose utilization. We have studied the effects of high (10^{-4} M) and low (10^{-9} M) concentrations of Etomoxir on reperfusion recovery of the isolated working hearts subjected to transient global ischemia followed by aerobic reperfusion.

Materials and Methods

Etomoxir was a generous gift of Dr. H. Wolf, Byk Gulden Pharmazeutika, Konstanz, FRG. [1-14C]palmitate (56.6 mCi/mmol) and D-[1-14C]glucose (1.5 mCi/mmol) was purchased from New England Nuclear, Boston, Massachusetts. Bovine serum albumin (fraction V) was obtained from Sigma Chemical, St. Louis, Missouri. All other chemicals were reagent grade.

Canulation of Hearts

Hearts from sodium pentobarbitol anesthetized male Wistar rats were excised and canulated as described previously and initially perfused retrogradely via the aorta for 10 minutes with Krebs-Henseleit buffer, pH 7.4, gassed with 95% O_2-5% CO_2 and containing 2.5 mM calcium and 11 mM glucose. During this time, the left atrium and the pulmonary artery were cannulated. Hearts were then perfused as working hearts with perfusate containing either glucose (11 mM) alone or glucose (11 mM) and palmitate (1.2 mM). A concentration of palmitate was chosen that is similar to plasma free fatty acid levels after ischemia. All perfusate included 3% bovine serum albumin, and palmitate, when used, was prebound to the albumin. Hearts were perfused during the initial work period at a left atrial filling pressure of 15 cm H_2O and a hydrostatic aortic afterload of 80 mm Hg. Myocardial oxygen consumption was determined with YSI micro oxygen electrodes that measured oxygen levels in perfusate entering the left atria and perfusate exiting the cannulated pulmonary artery. By simultaneous measurement of coronary flow, myocardial oxygen consumption was determined and expressed as micromoles O_2 consumed per minute per gram dry weight. Function was assessed by changes in aortic flow, heart rate, and peak systolic pressure development, which were monitored throughout the perfusion period.

Ischemic Heart Perfuisions

After 15 minutes of work, global ischemia was induced by clamping off left atrial and aortic flow. After 25 minutes of no-flow ischemia, left atrial and aortic flow was restored, and recovery of mechanical function was monitored for a further 30-minute period. The ischemic interval was chosen because it allowed complete recovery of function in glucose perfused hearts. Hearts were then frozen using Wollenberger clamps cooled to the temperature of liquid nitrogen. A number of hearts were also frozen following the 25-minute ischemic period. Etomoxir was administered either 5 minutes before ischemia or immediately before reperfusion of ischemic hearts.

Palmitate and Glucose Oxidation in Aerobic Hearts

Steady state oxidative rates of palmitate and glucose were performed as described previously. After a 10-minute washout perfusion, hearts were perfused in the working mode with recirculated Krebs-Henseleit buffer containing either 11 mM [1-14C]glucose, 1.2 mM palmitate, 11 mM [1-14C]glucose, or 1.2 mM [1-14C]palmitate with 11 mM glucose. All perfusions were performed in the presence of 3% albumin. Rates of [1-14C]palmitate or [1-14C]glucose oxidation were determined by measurement of steady state 14CO_2 production. Perfusion was continued for 60 minutes under conditions of high cardiac work (15 cm H_2O preload, 80 mm Hg afterload), and rates of palmitate oxidation were determined between 10 and 60 minutes, when rates of 14CO_2 production had reached a steady state. At the end of the perfusion, hearts were freeze-clamped with Wollenberger clamps cooled to the temperature of liquid nitrogen.

Tissue Workup

Frozen ventricular tissue was weighed and powdered in a mortar and pestle cooled to the temperature of liquid nitrogen. A portion of the powdered tissue was used to determine the dry-to-wet weight ratio. With this ratio, as well as with the total frozen ventricular weight and the weight of the dried atrial tissue, total dry weight of the heart was determined. Extraction of ATP, creatine phosphate, long chain acyl-CoA, and long chain acylcarnitine was as described previously. Measurement of ATP and creatine phosphate levels from perchloric acid extracts was determined with standard enzymatic assays. Extracted long chain acyl-CoA was hydrolyzed and free CoA measured fluorometrically. Extracted long chain acylcarnitine was also hydrolyzed and free carnitine measured radiometrically.

Statistical Analysis

Statistical analysis was performed using analysis of variance, followed by comparison of group means using group t tests. Statistical significance was set at p<0.05.
FIGURE 1. Effect of 10⁻⁹ M Etomoxir on heart function in isolated working hearts subjected to a 25-minute period of ischemia. Heart function, as measured by the heart rate-peak systolic pressure product, was measured in working hearts perfused at a left atrial filling pressure of 15 cm H₂O and a constant hydrostatic afterload of 80 mm Hg. Global ischemia was produced for a 25 minute period as described in the "Materials and Methods." All hearts were perfused with 11 mM glucose in either the presence or absence of 1.2 mM palmitate. Etomoxir was added to the perfusate 5 minutes prior to the initiation of ischemia. Values are the mean±SEM of at least five hearts in each group. *Significantly different from glucose-perfused hearts.

FIGURE 2. Effect of 10⁻⁶ M Etomoxir on reperfusion recovery of heart function in isolated working hearts subjected to a 25-minute period of ischemia. Heart function, as measured by the heart rate-peak systolic pressure product, was measured in working hearts perfused at a left atrial filling pressure of 15 cm H₂O and a constant hydrostatic afterload of 80 mm Hg. Global ischemia was produced for a 25-minute period, as described in "Materials and Methods." All hearts were perfused with 11 mM glucose in either the presence or absence of 1.2 mM palmitate. Etomoxir was added to the perfusate immediately prior to reperfusion of ischemic hearts. Values are the mean±SEM of at least five hearts in each group. *Significantly different from glucose-perfused control hearts. tSignificantly different from palmitate-perfused control hearts.

Results

Effects of Etomoxir on Fatty Acid Perfused Ischemic Hearts

Heart function, as measured by the heart rate peak systolic pressure product, was similar or slightly depressed during baseline aerobic perfusion if palmitate was present in the perfusion medium (Figures 1 and 2, Table 1). After 25 minutes of global no-flow ischemia, as we have previously demonstrated (G.D. Lopaschuk and M. Spafford, submitted manuscript), the presence of palmitate resulted in a significantly decreased postischemic recovery of heart rate and peak systolic pressure development (Table 1). A low concentration of Etomoxir (10⁻⁹ M) did not improve recovery in the palmitate-perfused hearts (Figure 1, Table 1). In fact, a significant decrease in heart rate was noted in Etomoxir-treated hearts, although the heart rate/peak systolic pressure product was not significantly different between the two groups. However, perfusion of hearts with this concentration of Etomoxir did decrease long chain acylcarboxilic acid and long chain acyl-CoA levels in palmitate-perfused hearts (Table 2). The decreases, which would be expected to occur if CPT 1 were inhibited, approached the levels seen in glucose perfused hearts. This suggests that this low dose of Etomoxir was sufficient to inhibit CPT 1 activity, yet no beneficial effect on reperfusion recovery of ischemic hearts was seen.

The higher concentration of Etomoxir (10⁻⁶ M) significantly increased recovery of both heart rate and peak systolic pressure development in palmitate-

<table>
<thead>
<tr>
<th>Perfusion condition</th>
<th>Heart rate (beats/min)</th>
<th>Peak systolic pressure (mm Hg)</th>
<th>HR×PSP×10⁻³ (beats · mm Hg · min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 mM glucose</td>
<td>240±9</td>
<td>87.1±2.7</td>
<td>20.9±0.9</td>
</tr>
<tr>
<td>no addition (n=8)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10⁻⁹ M Etomoxir (n=8)</td>
<td>203±5*</td>
<td>93.8±2.2</td>
<td>19.0±0.5</td>
</tr>
<tr>
<td>11 mM glucose, 1.2 mM palmitate</td>
<td>182±23*</td>
<td>72.7±10.2*</td>
<td>14.3±2.8*</td>
</tr>
<tr>
<td>no addition (n=9)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10⁻⁹ M Etomoxir (n=5)</td>
<td>112±30*</td>
<td>56.3±20.4*</td>
<td>10.8±3.8*</td>
</tr>
<tr>
<td>10⁻⁶ M Etomoxir (n=8)</td>
<td>210±11*</td>
<td>111.7±7.7*</td>
<td>23.4±1.8*</td>
</tr>
</tbody>
</table>

Heart function was measured in the same hearts perfused in Figures 1 and 2. Values are the mean±SEM of the number of hearts indicated in brackets. *Significantly different from glucose-perfused hearts. †Significantly different from palmitate-perfused hearts.

TABLE 1. Effect of Palmitate and Etomoxir on Heart Function Following 30 Minutes of Reperfusion of Isolated Working Hearts Subjected to a 25-Minute Period of Ischemia
TABLE 2. Effect of Etomoxir on Tissue Levels of Long Chain Acyl-CoA, Long Chain Acylcarnitine, ATP, and Creatine Phosphate Levels Following Reperfusion of Ischemic Hearts

<table>
<thead>
<tr>
<th>Perfusion condition</th>
<th>Long chain acyl-CoA (nmol/g dry wt)</th>
<th>Long chain acylcarnitine (nmol/g dry wt)</th>
<th>ATP (µmol/g dry wt)</th>
<th>Creatine phosphate (µmol/g dry wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 mM glucose</td>
<td>82±6</td>
<td>206±47</td>
<td>17.3±0.7</td>
<td>24.2±2.1</td>
</tr>
<tr>
<td>1.2 mM palmitate,</td>
<td>105±12</td>
<td>1,228±298*</td>
<td>13.2±0.8*</td>
<td>14.5±2.3*</td>
</tr>
<tr>
<td>11 mM glucose</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+10⁻⁹ M Etomoxir</td>
<td>59±9*†</td>
<td>345±28*†</td>
<td>11.2±1.7*</td>
<td>9.3±0.6*†</td>
</tr>
<tr>
<td>+10⁻⁶ M Etomoxir</td>
<td>198±17†</td>
<td>1,648±432†</td>
<td>23.1±3.5†</td>
<td>17.9±1.9†</td>
</tr>
</tbody>
</table>

Tissue levels of long chain acyl-CoA, long chain acylcarnitine, ATP, and creatine phosphate were measured at the end of the 30-minute reperfusion period of ischemic hearts. Values are the mean±SEM of five to eight hearts in each group.

*Significantly different from glucose control.
†Significantly different from palmitate control.

perfused hearts (Figure 2, Table 1). In contrast to the effects of 10⁻⁹ M Etomoxir, the increased recovery in palmitate-perfused hearts was not accompanied by a decrease in myocardial long chain acylcarnitine levels (Table 2). Rather, a significant increase in long chain acyl-CoA levels was seen. These observations contrast with the metabolic effects of 10⁻⁹ M Etomoxir. This difference may be explained by an inhibition of CPT 2 at 10⁻⁶ M Etomoxir, the net effect of which would be to increase both cytosolic long chain acylcarnitine and long chain acyl-CoA. Thus, Etomoxir may inhibit CPT 1 at low concentrations and CPT 2 at higher concentrations. The latter effect may be associated with improved recovery after global ischemia.

Etomoxir Effects on Myocardial Oxygen Consumption

As shown in Figures 3B and 4B, use of palmitate as a metabolic substrate results in a small increase in oxygen consumption corrected for work. Oxygen consumption, however, was significantly different at only one time point in each perfusion group. Measurements of absolute levels of oxygen consumed (as based on micromoles per gram dry weight per minute) were lower in palmitate-perfused hearts compared with control (a reflection of the decreased work performed by these hearts). Addition of 10⁻⁹ M Etomoxir to the perfusate resulted in a decrease in total oxygen consumption although no changes in oxygen consumption were noted when corrected for workload differences. Addition of 10⁻⁶ M Etomoxir resulted in a small, but significant, increase in total oxygen consumption in palmitate-perfused hearts. When adjusted for the increased work performed during reperfusion, a significant decrease in oxygen consumption was noted. Thus, at this dose, Etomoxir effectively decreases oxygen consumption/unit work in palmitate perfused hearts to levels similar to those seen in glucose perfused hearts.

Etomoxir Effects on High Energy Phosphates

The effects of Etomoxir on recovery of high energy phosphate levels was determined after 30 minutes of reperfusion recovery of ischemic hearts. Following ischemia, levels of ATP in glucose- and palmitate-perfused hearts were 10.0±0.9 and 12.0±0.9 µmol/g dry wt, respectively (normal levels are 25 µmol/g dry wt). Following 30 minutes of reperfusion with glucose, a significant increase in ATP levels from immediate postischemic values was seen (Table 2). In contrast, no increase was seen
following 30 minutes of reperfusion in palmitate perfused hearts. Etomoxir (10^{-6} M) did not increase ATP levels following reperfusion of palmitate perfused hearts, but Etomoxir (10^{-6} M) produced a significant recovery of ATP. Creatine phosphate levels followed a similar trend in these hearts. Following ischemia, levels were 3.7±0.6 and 5.1±0.7 μmol/g dry wt in glucose and palmitate perfused hearts, respectively (normal levels are 35 μmol/g dry wt). Reperfusion with glucose increased creatine phosphate levels to a greater extent than palmitate perfusion (Table 2). Addition of 10^{-6} M Etomoxir to palmitate-perfused hearts resulted in lower creatine phosphate levels following reperfusion, while 10^{-6} M Etomoxir significantly increased creatine phosphate levels compared with palmitate alone.

**Etomoxir Effects on Myocardial Glucose and Palmitate Oxidation**

Ideally, it would be desirable to determine directly the effect of Etomoxir on glucose and palmitate oxidation in postischemic hearts during the reperfusion period. However, measured oxidative rates under non-steady state conditions are difficult to interpret due to the contribution of intracellular glucose and fatty acid to overall oxidative metabolism (i.e., the labeled substrate is not in equilibrium with intracellular unlabeled substrate). Similarly, changes in work performed by the heart under non-steady state conditions can markedly alter oxidative metabolism. During ischemia and initial reperfusion, the heart is not in a steady state. Therefore, we looked at the effect of both low and high concentrations of Etomoxir on palmitate and glucose oxidation in steady state aerobic hearts not subjected to ischemia. As shown in Table 3, palmitate results in a marked decrease in steady state glucose oxidation. At the low dose of Etomoxir (10^{-6} M) no significant effect on glucose oxidation was seen in either the presence or absence of palmitate. At this dose, Etomoxir also had no effect on palmitate oxidation (Table 4). At a high concentration (10^{-6} M) Etomoxir results in a small increase in palmitate oxidation. This dose of Etomoxir results in a much larger increase in glucose oxidation, which occurred both in the presence and absence of palmitate (Table 3).

**Discussion**

Recent studies have demonstrated beneficial effects of CPT 1 inhibitors in ischemic hearts. Paulson et al.\(^\text{16}\) showed that POCA could protect isolated perfused rat hearts from ischemia. Molaparast-Saless et al.\(^\text{18}\) demonstrated a protective effect of oxefinone in situ pig hearts. In contrast, Seitelberger et al.\(^\text{27}\) failed to demonstrate a protec-
et effective effect of CPT 1 agents. In this study we looked at the effects of a potent CPT 1 inhibitor directly on fatty acid-induced ischemic injury. We demonstrate that Etomoxir can prevent the fatty acid-induced failure of ischemic hearts. Unlike other studies, we found that recovery of heart function was not correlated with long chain acylcarnitine levels. Direct measurement of palmitate oxidation in aerobic hearts also demonstrates that doses of Etomoxir that protect the ischemic heart do not decrease palmitate oxidation. Thus, the protective effect may be related to its ability to stimulate glucose oxidation.

Etomoxir and the less potent analogue POCA both inhibit CPT 1 in vitro. These agents are converted intracellularly to their CoA esters, which then inactivate mitochondrial CPT 1 in a time- and dose-dependent manner. In ischemic hearts, POCA lowers myocardial long chain acylcarnitine levels, the product of CPT 1. Decreases in myocardial levels of these potentially harmful fatty acid esters are thought to account for the protective effect of the CPT 1 inhibitors. The dose-response relation between POCA-induced changes in myocardial acylcarnitine level and myocardial protection has not been described. The effect of these agents has also not been described in hearts in which the direct effect of high concentrations of fatty acids on ischemic injury was studied. In our study, we demonstrate a dissociation between Etomoxir’s protective effect and Etomoxir’s effect on myocardial acylcarnitine levels. At a very low dose (10^{-9} M), Etomoxir appears to inhibit CPT 1 in ischemic hearts, as measured by a decrease in long chain acylcarnitine levels. However, at this dose no protective effect is seen during reperfusion with fatty acids. At higher doses (10^{-6} M) in which protection occurs, Etomoxir resulted in a small increase in long chain acylcarnitine levels and a significant increase in long chain acyl-CoA levels. This possibly results from CPT 2 inhibition, which would explain the observed increase in these fatty acid intermediates. If CPT 2 were inhibited, cytosolic long chain acyl-CoA should increase and the decrease in long chain acylcarnitine due to CPT 1 inhibition would be overcome. No studies have yet been published that determine if higher doses of Etomoxir will inhibit CPT 2 in vitro.

Etomoxir is presently being tested as an antidiabetic agent due to its ability to increase glucose utilization. The increase in myocardial glucose oxidation we observed in aerobic hearts may explain the beneficial effects of Etomoxir in ischemic hearts. We suggest that decreased fatty acid transport into mitochondria by Etomoxir results in a lowering of TCA cycle intermediates such as citrate and acetyl-CoA. Lowering citrate would result in a decreased inhibition of phosphofructokinase, while lowering acetyl-CoA should result in increased glycolytic flux and glucose oxidation. We are presently measuring these metabolites following similar perfusion protocols.

In isolated mitochondrial preparations, CPT 1 inhibition decreases fatty acid oxidation. However, in our intact hearts, even a high dose of Etomoxir does not significantly decrease palmitate oxidative rates. To our knowledge, no other study has looked at the effect of POCA or Etomoxir on palmitate oxidation in intact hearts. In nonischemic perfused hearts, a decrease in myocardial lipolysis was observed with POCA, although these hearts were not perfused with fatty acids. Oxefencine has been shown to inhibit palmitate oxidation although as of yet we have not tried this agent under our perfusion conditions. In our perfusions, a high concentration of palmitate was used since circulat-

### Table 4: Effect of Etomoxir on Steady State Palmitate Oxidation in Aerobic Hearts

<table>
<thead>
<tr>
<th>Perfusion condition</th>
<th>(^{14})CO(_2) production ((\mu)mol palmitate/g dry wt/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2 mM palmitate, 11 mM glucose</td>
<td>0.45±0.05</td>
</tr>
<tr>
<td>+10^{-9} M Etomoxir</td>
<td>0.50±0.08</td>
</tr>
<tr>
<td>+10^{-6} M Etomoxir</td>
<td>0.60±0.06*</td>
</tr>
</tbody>
</table>

Palmitate oxidation was determined by measuring \(^{14}\)CO\(_2\) production in hearts perfused with 11 mM glucose [1-\(^{14}\)C]palmitate (1.2 mM). Hearts were perfused for 60 minutes at a 15 cm H\(_2\)O left atrial filling pressure and 80 mm Hg hydrostatic afterload. Steady state \(^{14}\)CO\(_2\) production was determined between 20 and 60 minutes. Values are the mean±SEM of six to eight hearts in each group.

*Significantly different from glucose control.

### Table 5: Effect of Etomoxir on Tissue Levels of Long Chain Acyl-CoA and Long Chain Acylcarnitine in Aerobic Hearts

<table>
<thead>
<tr>
<th>Perfusion condition</th>
<th>Long chain acyl-CoA (nmol/g dry wt)</th>
<th>Long chain acylcarnitine (nmol/g dry wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11 mM glucose</td>
<td>54±1</td>
<td>642±120</td>
</tr>
<tr>
<td>+10^{-9} M Etomoxir</td>
<td>47±2*</td>
<td>738±163</td>
</tr>
<tr>
<td>+10^{-6} M Etomoxir</td>
<td>76±8*</td>
<td>761±110</td>
</tr>
<tr>
<td>1.2 mM palmitate, 11 mM glucose</td>
<td>139±13*</td>
<td>1,671±266*</td>
</tr>
<tr>
<td>+10^{-9} M Etomoxir</td>
<td>76±9*†</td>
<td>1,221±157*</td>
</tr>
<tr>
<td>+10^{-6} M Etomoxir</td>
<td>98±11*</td>
<td>1,580±264*</td>
</tr>
</tbody>
</table>

Tissue levels of long chain acyl-CoA and long chain acylcarnitine were measured at the end of the 60-minute perfusion period of aerobic hearts. Values are the mean±SEM of five to seven hearts in each group.

*Significantly different from glucose controls.
†Significantly different from palmitate controls.
ing fatty acid increases during ischemia.\textsuperscript{1,26} It would be expected that this high concentration of fatty acid could compete with Etomoxir at the level of acyl-CoA synthetase. Although oxidative metabolism is not inhibited, it is conceivable that intramitochondrial levels of fatty acid intermediates are decreased by Etomoxir treatment. This possibility has not been addressed in our study.

In these studies, 10\textsuperscript{–6} M Etomoxir increases glucose oxidation in aerobic hearts. An important question is what effect this dose of Etomoxir has on glucose oxidation during reperfusion of ischemic hearts. Reperfusion of ischemic myocardium will enhance glucose uptake and utilization and decrease fatty acid utilization.\textsuperscript{30} During ischemia, the decrease in oxidative metabolism will decrease glucose utilization, but not to the same degree as the decrease in free fatty acid utilization.\textsuperscript{31–33} This relative increase in glucose utilization in ischemic and reperfused myocardium is thought to benefit the cell by decreasing oxygen consumption at a given workload. In our hearts, 10\textsuperscript{–6} M Etomoxir did result in a decrease in oxygen consumption per unit work, although whether this was due to an increase in glucose utilization remains to be determined. Since oxidative rates are in large part dependent on heart work, maintenance of heart work in a steady state is necessary to accurately measure non–work dependent changes in glucose oxidation. This could not be achieved during the 30-minute reperfusion period used in our studies, although longer periods of reperfusion may have approximated a steady state and facilitated detection of non–work dependent changes in glucose oxidation.

In summary, we demonstrate that Etomoxir significantly improves myocardial function during reperfusion of palmitate perfused ischemic hearts. This effect was concentration dependent and was not correlated with a decrease in myocardial long chain acylcarnitine levels. A decrease in oxygen consumption per unit work, due to an increase in glucose utilization, may account for the beneficial effect of Etomoxir.

Acknowledgment

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References

6. Oliver MF: Metabolic response during impeding myocardial infarction: II. Clinical implications. Circulation 1978;45:491–500
12. Lamers MJM, Hulsmann WC: Inhibition of (Na\textsuperscript{+}–K\textsuperscript{+})-stimulated ATPase by palmitoyl-carnitine: Potentiation by propanolol. J Mol Cell Cardiol 1977;9:343–346
27. Seitelberger R, Kraupp O, Winkler M, Brugger G, Raberger M: Effect of Etomoxir on metabolism and regional function in the under-


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