The Antianginal Agent Trimetazidine Does Not Exert Its Functional Benefit via Inhibition of Mitochondrial Long-Chain 3-Ketoacyl Coenzyme A Thiolase

Alan MacInnes, David A. Fairman, Peter Binding, Jo-ann Rhodes, Michael J. Wyatt, Anne Phelan, Peter S. Haddock, Eric H. Karran

Abstract—Trimetazidine acts as an effective antianginal clinical agent by modulating cardiac energy metabolism. Recent published data support the hypothesis that trimetazidine selectively inhibits long-chain 3-ketoacyl CoA thiolase (LC 3-KAT), thereby reducing fatty acid oxidation resulting in clinical benefit. The aim of this study was to assess whether trimetazidine and ranolazine, which may also act as a metabolic modulator, are specific inhibitors of LC 3-KAT. We have demonstrated that trimetazidine and ranolazine do not inhibit crude and purified rat heart or recombinant human LC 3-KAT by methods that both assess the ability of LC 3-KAT to turnover specific substrate, and LC 3-KAT activity as a functional component of intact cellular oxidation. Furthermore, we have demonstrated that trimetazidine does not inhibit any component of β-oxidation in an isolated human cardiomyocyte cell line. Ranolazine, however, did demonstrate a partial inhibition of β-oxidation in a dose-dependent manner (12% at 100 μmol/L and 30% at 300 μmol/L). Both trimetazidine (10 μmol/L) and ranolazine (20 μmol/L) improved the recovery of cardiac function after a period of no flow ischemia in the isolated working rat heart perfused with a buffer containing a relatively high concentration (1.2 mmol/L) of free fatty acid. In summary, both trimetazidine and ranolazine were able to improve ischemic cardiac function but inhibition of LC 3-KAT is not part of their mechanism of action. The full text of this article is available online at http://www.circresaha.org.

Key Words: cardiac metabolism ischemia trimetazidine
Trifunctional protein complex (TFP) consists of a CoA dehydrogenase, an enoyl CoA hydratase, and a 3-hydroxyacyl CoA dehydrogenase. TFP reduces superoxide free radicals and maintains the enoyl CoA hydratase and L-3-hydroxyacyl CoA dehydrogenase activities, whereas the β-subunit contains the 3-ketoacyl CoA dehydrogenase activity.

Several double-blinded clinical trials have shown a substantial benefit with trimetazidine in patients with stable angina, at least equivalent to propranolol and nifedipine and additive in combination with diltiazem. The antianginal agent ranolazine, described as a partial fatty acid oxidation inhibitor (pFOXi), also appears to act as a metabolic modulator. Ranolazine exerts beneficial effects on cellular acidosis during low-flow simulated ischemia and is cardioprotective in in vitro models of ischemic injury. It has been proposed that these effects derive from inhibition of the mitochondrial LC 3-KAT, consequent inhibition of β-oxidation and re-coupling of glucose oxidation. β-Oxidation consists of four enzymatic steps. An initial acyl CoA dehydrogenase produces substrate for entry into the trifunctional protein complex (TFP). TFP consists of a multimeric α- and β-subunit complex. The α-subunit contains the enoyl CoA hydratase and L-3-hydroxyacyl CoA dehydrogenase activities, whereas the β-subunit contains the LC 3-KAT activity.

Several double-blinded clinical trials have shown a substantial benefit with trimetazidine in patients with stable angina, at least equivalent to propranolol and nifedipine and additive in combination with diltiazem. The efficacy of trimetazidine is considered different from traditional antianginal therapy in that benefit is achieved without any hemodynamic effects. Trimetazidine’s mechanism of action remains ill-defined, with (1) direct effects on cardiac sodium current, reducing the production of superoxide free radicals, synthesis and turnover of complex lipids, and (4) binding to a mitochondrial transition pore binding site all having been subject to investigation. However, the present view is that trimetazidine directly inhibits LC 3-KAT and acts as a metabolic modulator.

The antianginal agent ranolazine, described as a partial fatty acid oxidation inhibitor (pFOXi), also appears to act as a metabolic modulator. Ranolazine exerts beneficial effects in reperfused ischemic hearts by stimulating glucose oxidation as a consequence of reducing fatty acid oxidation. More recently, ranolazine has demonstrated antianginal efficacy alone and in combination with existing therapy, without any deleterious alterations in rate pressure product or coronary blood flow. Despite being termed a pFOXi, the exact mechanism of action of ranolazine has yet to be determined.

The purpose of this study was to assess directly whether trimetazidine and ranolazine exert their beneficial effects on mitochondrial substrate oxidation and cardiac function by selectively inhibiting LC 3-KAT. The effects of these agents was assessed on (1) the enzymatic activities of rat LC 3-KAT (purified from tissue) and human recombinant LC 3KAT (expressed and purified), (2) β-oxidation in a human cardiomyocyte line, and (3) the isolated working heart after a period of no-flow ischemia.

Materials and Methods

Protein Expression, Characterization, and Purification

TFP containing LC 3-KAT was purified from frozen rat heart tissue by a modification of the method described by Carpenter et al. The mature forms of TFP-α and TFP-β were amplified by polymerase chain reaction using clones 8123703 and 4767040 (Incyte Corporation), respectively, as templates and the following primer pairs: α-forward, GTGTCGACAAACCAGAACCATATT, and α-reverse, TGCTGGAATCTGGAAGACTCTTTGT-TAGGGCT; β-forward, CTCGAGTCGAGCCGCTGTCCA-GACCAAA, and β-reverse, CTCGAGTTATTTTTGGATAAAGCT-TCCACTAT. PCR products were sequence validated and cloned into pET bacterial expression vectors (Novagen) to include N-terminal affinity tags: S-· tag for TFP-α (in pET29a) and (His)6 tag for TFP-β (in pET14b). BL21 (DE3) pLysS cells transformed with the TFP expression constructs were grown in LB medium supplemented with 34 μg/mL chloramphenicol plus 50 μg kanamycin (pET29a_TFP-α construct) or 50 μg/mL carbenicillin (pET14b_TFP-β construct). Cells were grown at 37°C on an orbital shaker at 225 rpm, to an OD600 value of 0.6 for soluble protein expression. Isopropyl-β-D-thiogalactopyranoside (IPTG) was then added to induce protein expression that was allowed to proceed at 23°C for 2 hours. Cells were harvested by centrifugation at 10 700g for 30 minutes at 4°C, and were resuspended in lysis buffer.
Biochemical Analysis
The enzymatic activity of LC 3-KAT was assayed using two methods from (1) crude rat heart mitochondrial homogenate (crTFP), (2) purified rat heart trifunctional protein (prTFP), or (3) recombinant human trifunctional protein (rhTFP).

Method 1 assayed the turnover by LC 3-KAT of specific 3-ketoacyl CoA substrate that was produced in situ (Figure 1). Buffer constituents were as described by Wanders et al25 for the determination of thiolase (EC 2.3.1.16) activity without KCl, and at pH 9.0. Reactions were performed in 5-mL batches at 30°C and absorbance changes detected using a Molecular Devices SPECTRAMAX PLUS. Palmitoyl CoA (50 μmol/L) was converted to the trans-Δ-trans form using 0.1 U/mL acyl CoA oxidase (EC 1.3.3.6) (detected as an increase in absorption at 280 nm). rhTFP subunit was added, and the enoyl CoA hydrolase (EC 4.2.1.7) activity measured as a decrease in absorption at 280 nm.26 NAD (2 mM) was added and the L-3-hydroxyacetyl CoA dehydrogenase (EC 1.1.1.35) activity measured as an increase in absorbance at 340 nm26 until the change in absorbance became asymptotic (typically equivalent to 0.40 to 0.45 μmol/L/3-ketoacyl CoA). The mixture was boiled for 30 seconds to denature proteins and centrifuged (10 minutes at 13,000 × g) to recover the 3-ketoacyl CoA in the supernatant. Ninety microliters of the supernatant was added to each well of a 96-well plate. Vehicle (10 μL of pH 7.3 Tris buffer, to 0.1 OD units), to 0.1 OD units in

Whole Cell-Based β-Oxidation
Cardiomyocytes (Girardi cells; CCL 27) (ECACC) were cultured as described previously27 except that cells were seeded into 12-well plates 72 hours before use and 1 mmol/L I-carnitine was added.28 Plates were washed twice with PBS (with calcium and magnesium). Compounds (either trimetazidine, ranolazine, or oxefunicline) were added and preincubated for 15 minutes before the addition of 13C-palmitate (6 mmol/L in 15% BSA) to give a final concentration of 1.2 mmol/L palmitate. At 60 minutes, the medium was aspirated, 200 μL of 0.5 mol/L perchloric acid (PCA) added to each well, and the plates frozen at −80°C until analysis. Acetyl-CoA derived from β-oxidation of the labeled palmitate is utilized by the cells for citrate synthesis or incorporated into acetyl-l-carnitine.29 The accumulation of 13C-acetyl-L-carnitine was quantitated as a measure of the rate of β-oxidation. Acetyl-L-carnitine, L-carnitine, and labeled acetyl-L-carnitine were measured in neutralized PCA extracts using a Shimadzu QP8000 single quadruple LCMS. Injections (5 μL) of each sample were analyzed for the corresponding positive parent ions of the three species (m/z 204.1, 162.1, and 206.1, respectively) using single ion monitoring and quantified using the area under the curve for each ion current.

Statistics
All data are presented as the group mean ± SEM. For the biochemical analysis, t tests were only performed at the highest compound concentration. For the cell-based assay analysis of variance (ANOVA) was used to compare treatments to vehicle using a blocked experimental design. For the working heart preparation, ANOVA was used to compare treatments while the average of the three baseline values was used as a covariate.

Results
Trimetazidine Does Not Inhibit LC 3-KAT
The TFP of mitochondrial β-oxidation contains an α and β subunit. The enoyl CoA hydratase and L-3 hydroxyacyl CoA dehydrogenase activities are contained in the α-subunit, whereas the LC 3-KAT activity is contained in the β-subunit. Our aim was to assess the specific inhibition by agents of LC 3-KAT. Therefore, only fractions of crTFP, prTFP, and rhTFP that demonstrated activity for the long-chain substrate (palmitoyl CoA) but were devoid of short chain substrate (butyryl CoA)-dependent hydratase, dehydrogenase, and thiolase activity were used (data not shown).

The addition of CoA to a reaction mixture containing 3-ketoacyl CoA and either crTFP, prTFP, or rhTFP caused a decrease in absorbance at 303 nm, representing a thiolase-dependent decrease in 3-ketoacyl CoA (data not shown): the effects of compounds to inhibit LC 3-KAT was expressed as
the percentage change in absorbance compared with vehicle control (Figures 3A through 3C). Trimetazidine (0.1 to 100 μmol/L) and ranolazine (0.1 to 100 μmol/L) failed to inhibit any of the preparations of LC 3-KAT. The concentration ranges for trimetazidine and ranolazine were taken from Kantor et al12 who report the IC50 of trimetazidine as 75 nmol/L. In our studies, the highest concentrations used for trimetazidine and ranolazine were limited by their solubility. Acetyl CoA, however, a known inhibitor of LC 3-KAT,32 dose-dependently inhibited all three LC 3-KAT activities with equal potency (P<0.05 at 2 mmol/L).

β-Oxidation is a highly adaptive and tightly regulated process sensitive to small changes in concentrations of all components of the pathway. Because our first experiments focused on the thiolase and final step of the pathway, we also assessed the ability of trimetazidine and ranolazine to inhibit LC 3-KAT as a functional component of intact β-oxidation (Figure 4). The addition of CoA caused a shift in the equilibrium of the dehydrogenase reaction by removing the product inhibition of 3-ketoacyl CoA on the L-3-hydroxyacyl CoA dehydrogenase enzyme. LC 3-KAT activity was assayed as an increase in dehydrogenase activity, and the effects of compounds expressed as a percentage of the control group. Trimetazidine (0.1 to 100 μmol/L) and ranolazine (0.1 to 100 μmol/L) did not inhibit LC 3-KAT; however, acetyl CoA (0.03 to 2 mmol/L) did significantly inhibit LC 3-KAT in a dose-dependent manner (P<0.05 at 2 mmol/L). Benztropin (0.3 to 2 mmol/L), a known inhibitor of β-oxidation33 used as a positive control to validate the methodology, dose-dependently inhibited LC 3-KAT (P<0.05 at 2 mmol/L) (Figure 4).

Trimetazidine Does Not Inhibit β-Oxidation in Cardiomyocytes

The effects of compounds on flux through β-oxidation was assessed using intact human cardiomyocytes and quantified by analysis of the 13C-palmitate-dependent accumulation of 13C-acetyl-L-carnitine (Figure 5 and Table 1). The formation of 13C-acetyl-L-carnitine was shown to be solely dependent on 13C-palmitate by demonstrating zero production of 13C-acetyl-L-carnitine in the presence of 13C-palmitate (data not shown). The addition of 1.2 mmol/L 13C-palmitate caused an accumulation of 235±6 μg/μL 13C-acetyl-L-carnitine after 60 minutes. Preincubation with trimetazidine (10 to 300 μmol/L) had no effect on the accumulation of 13C-acetyl-L-carnitine. Preincubation with ranolazine (10 to 300 μmol/L), however, caused a dose-dependent inhibition of the accumulation of 13C-acetyl-L-carnitine. Ranolazine (100 μmol/L) reduced β-oxidation of 13C-palmitate by ∼12% (P<0.05), whereas 300 μmol/L ranolazine caused a ∼30% attenuation (P<0.001). The selective CPT-I inhibitor, oxfenicine, shown previously to inhibit β-oxidation,34 was used as a positive control to validate the assay and detection systems. Oxfenicine (10 μmol/L) significantly attenuated the accumulation of 13C-acetyl-L-carnitine by ∼67% (P<0.001), confirming that this assay system is sensitive to inhibitors of mitochondrial fatty acid metabolism.

Trimetazidine Improves Cardiac Function

Isolated working rat hearts were subjected to a 20-minute period of global no-flow ischemia. The recovery of cardiac function in the presence of trimetazidine (10 μmol/L), ranolazine (20 μmol/L), and DCA (1 mmol/L) was followed during a 40-minute reperfusion period (Figure 6 and Table 2).
There was no significant difference (P=0.926) in cardiac function during the preischemic baseline period between any of the treatment groups (data not shown). After a 20-minute period of no-flow ischemia, isolated hearts that were perfused with a buffer containing 5.5 mmol/L glucose recovered to values similar to those before ischemia. However, the addition of 1.2 mmol/L palmitate significantly depressed the postischemic recovery of cardiac function by ~70%. None of the compounds significantly changed heart rate, peak systolic pressure, developed pressure, cardiac output, or cardiac work during the preischemic period (data not shown). All three agents, however, significantly improved the recovery of cardiac function during the reperfusion period in the presence of 1.2 mmol/L palmitate (P<0.001 for area under the curve [AUC] values) (Table 2). At the end of the reperfusion period, hearts perfused with trimetazidine, ranolazine, or DCA recovered to a degree that was not significantly different to control hearts perfused in the absence of 1.2 mmol/L palmitate (P>0.05) (Figure 6). These data are in agreement with previous literature for trimetazidine9 and ranolazine35 under similar conditions, confirming that both trimetazidine and ranolazine are cardioprotective after exposure to a period of ischemia even under conditions of high circulating concentrations of FFA.

### Table 1. Effects of Trimetazidine, Ranolazine, and Oxfenicine on 13C-Acetyl-L-Carnitine Accumulation in Girardi Cardiomyocytes

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean, pg/μL</th>
<th>Difference to Vehicle, pg/μL</th>
<th>95% Confidence Intervals</th>
<th>P Value Versus Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>235</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100 μmol/L trimetazidine</td>
<td>258</td>
<td>23</td>
<td>-3, 49</td>
<td>0.077</td>
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<tr>
<td>30 μmol/L ranolazine</td>
<td>233</td>
<td>-2</td>
<td>-28, 23</td>
<td>0.843</td>
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<tr>
<td>100 μmol/L ranolazine</td>
<td>207</td>
<td>-28</td>
<td>-53, -2</td>
<td>0.036</td>
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<tr>
<td>300 μmol/L ranolazine</td>
<td>163</td>
<td>-72</td>
<td>-97, -46</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>10 μmol/L oxfenicine</td>
<td>77</td>
<td>-158</td>
<td>-184, -133</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

*Values are for comparison of treatments to vehicle using one-way ANOVA adjusted for 3 data blocks; n=3 for all treatments and n=9 for vehicle.

### Discussion

The effectiveness of trimetazidine as an antianginal agent is undisputed: trimetazidine demonstrates equivalent antiischemic efficacy to current therapy and additive efficacy in combination with current antianginal agents. Trimetazidine is also different from traditional antianginal therapy in that efficacy is not associated with any hemodynamic effects.13–16 However, the mechanism of trimetazidine’s action is unresolved. Recently, Kantor et al12 suggested that trimetazidine selectively inhibited LC 3-KAT and thereby reduced fatty acid oxidation. The aim of this study was to assess whether LC 3-KAT is the pharmacological target for trimetazidine, and to ascertain whether ranolazine, also referred to as a metabolic modulator or pFOX1, acts similarly. Importantly, our data demonstrate that trimetazidine and ranolazine are not inhibitors of LC 3-KAT.

We used recombinant human trifunctional protein complex in addition to a crude mitochondrial homogenate and protein isolated and purified from frozen rat heart tissue to assess the ability of these agents to inhibit LC 3-KAT. The assay systems used were confirmed to be measuring LC 3-KAT activity because they were CoA- and 3-ketoacyl CoA-dependent. We were unable to inhibit LC 3-KAT in any form with either trimetazidine or ranolazine over a wide concentr...
tation range (Figures 3 and 4). All forms of LC 3-KAT were, however, dose-dependently inhibited by acetyl CoA. Acetyl CoA serves as a sensor for the β-oxidation pathway that will inhibit the continued flux through this system when products are plentiful. Thus, our ability to demonstrate a dose-dependent inhibition of all three forms of LC 3-KAT with acetyl CoA and the fact that this inhibition is dependent on the presence of CoA, confirms the assay is sensitive to agents that inhibit this particular enzyme. Additionally, we were able to detect inhibition of flux through β-oxidation by using the known inhibitor of β-oxidation, benzotript, further confirming that our assay system was sensitive to inhibition. Therefore, we have demonstrated (and in more than one species) that neither trimetazidine nor ranolazine exert their cardioprotective effects by selectively inhibiting LC 3-KAT. This directly contrasts with the published findings of Kantor et al.12

We therefore examined whether trimetazidine or ranolazine act to inhibit β-oxidation via a different mechanism in a whole human cardiomyocyte assay. Girardi human atrial cells preferentially utilize glycolytic substrates. However, by incubating these cells with L-carnitine for 72 hours, we demonstrated, in a similar manner to Molstad et al,28 that substrate preference is shifted from a glycolytic to a fatty acid source. The assay assessed the overall flux through β-oxidation by monitoring the linear oxidation of 13C-palmitate to 13C-acetyl-L-carnitine over a 60-minute time period. We used the standard CPT-I inhibitor, oxfenicine, to demonstrate the assay system was capable of detecting inhibitors of β-oxidation. As illustrated in Figure 5 and Table 1, trimetazidine did not inhibit the accumulation of 13C-acetyl-L-carnitine up to concentrations of 300 μmol/L, demonstrating that in addition to not inhibiting LC 3-KAT, trimetazidine was unable to inhibit any other component of the β-oxidation pathway as present in these cells. The pFOXi ranolazine did, however, demonstrate a partial inhibition of this process in a dose-dependent manner, albeit at higher concentrations than those associated with improvement in cardiac function in isolated organ preparations.36

Having demonstrated a lack of effect in whole cells, we then used the isolated working rat heart model to assess cardiac function in the presence of these agents. By using a modest period of global no-flow ischemia, coupled with a perfusion media that contains a high concentration of FFA (1.2 mmol/L palmitate), we have reproduced key elements of the pathology associated with cardiac ischemia in vivo. As a result, recovery of cardiac function, in this case expressed as cardiac work, was reduced by ~70% compared with that of hearts exposed to buffer containing zero FFA. In this model, therefore, cardiac dysfunction is driven by the presence of high concentrations of FFA. As such, it provides an excellent system for investigating agents thought to improve function by affecting fatty acid metabolism. This experimental paradigm was validated by demonstrating that DCA, a metabolic modulator known to increase pyruvate oxidation via activation of PDC, improved the recovery of function to control levels (in the absence of FFA). We have demonstrated that trimetazidine and ranolazine significantly improve the recovery of function to a similar extent as DCA, with no deleterious impact on heart rate or coronary blood flow. These data, therefore, suggest that trimetazidine and ranolazine are exerting their benefit by some mechanism other than causing coronary vasodilatation. It is acknowledged that concentrations of trimetazidine used in our working heart studies were in excess of free plasma concentrations necessary to achieve anti-anginal benefit in the clinic. These concentrations, however, are in agreement with previously published studies.9,35

Our data suggest, therefore, that the clinical efficacy associated with trimetazidine is associated with a mechanism of action unrelated to inhibition of any part of the β-oxidation pathway, although various hypotheses exist in the literature. For example, others have suggested effects on intracellular calcium homeostasis through binding of trimetazidine to the mitochondrial permeability transition pore,29 although there is very little data to support this.

In summary, we demonstrate that although ranolazine may assist in the recovery of cardiac function after ischemia by acting as a pFOXi, it is not via inhibition of LC 3-KAT. Additionally, and in contrast to the findings of Kantor et al,12 we demonstrate that although trimetazidine does improve the recovery of cardiac function after a period of ischemia, it does not achieve this through inhibition of LC 3-KAT nor does it interfere with any component of β-oxidation that we have assayed: pure and crude enzyme preparations and whole cell β-oxidation. Trimetazidine and ranolazine failed to demonstrate inhibitory activity of LC 3-KAT at concentrations 10-fold greater than the concentrations used to demonstrate functional benefit in the working heart model. Further studies will be required to establish molecular targets for the significant antianginal effects of trimetazidine and ranolazine.

Acknowledgments

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