Metabolic Modulator Perhexiline Corrects Energy Deficiency and Improves Exercise Capacity in Symptomatic Hypertrophic Cardiomyopathy

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Background—Hypertrophic cardiomyopathy patients exhibit myocardial energetic impairment, but a causative role for this energy deficiency in the pathophysiology of hypertrophic cardiomyopathy remains unproven. We hypothesized that the metabolic modulator perhexiline would ameliorate myocardial energy deficiency and thereby improve diastolic function and exercise capacity.

Methods and Results—Forty-six consecutive patients with symptomatic exercise limitation (peak \(\dot{V}O_2 < 75\%\) of predicted) caused by nonobstructive hypertrophic cardiomyopathy (mean age, 55 ± 0.26 years) were randomized to perhexiline 100 mg (n = 24) or placebo (n = 22). Myocardial ratio of phosphocreatine to adenosine triphosphate, an established marker of cardiac energetic status, as measured by \(^{31}\)P magnetic resonance spectroscopy, left ventricular diastolic filling (heart rate normalized time to peak filling) at rest and during exercise using radionuclide ventriculography, peak \(\dot{V}O_2\), symptoms, quality of life, and serum metabolites were assessed at baseline and study end (4.6 ± 1.8 months). Perhexiline improved myocardial ratios of phosphocreatine to adenosine triphosphate (from 1.27 ± 0.02 to 1.73 ± 0.02 versus 1.29 ± 0.01 to 1.23 ± 0.01; \(P = 0.003\)) and normalized the abnormal prolongation of heart rate normalized time to peak filling between rest and exercise (0.11 ± 0.008 to −0.01 ± 0.005 versus 0.15 ± 0.007 to 0.11 ± 0.008 second; \(P = 0.03\)). These changes were accompanied by an improvement in primary end point (peak \(\dot{V}O_2\) (22.2 ± 0.3 to 22.3 ± 0.3 mL·kg\(^{-1}\)·min\(^{-1}\); \(P = 0.003\)) and New York Heart Association class (\(P < 0.001\)) (all \(P\) values ANCOVA, perhexiline versus placebo).

Conclusions—In symptomatic hypertrophic cardiomyopathy, perhexiline, a modulator of substrate metabolism, ameliorates cardiac energetic impairment, corrects diastolic dysfunction, and increases exercise capacity. This study supports the hypothesis that energy deficiency contributes to the pathophysiology and provides a rationale for further consideration of metabolic therapies in hypertrophic cardiomyopathy.

Clinical Trial Registration—URL: http://www.clinicaltrials.gov. Unique identifier: NCT00500552.

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Key Words: cardiomyopathy ■ exercise ■ hypertrophy ■ metabolism ■ spectroscopy

Hypertrophic cardiomyopathy (HCM) is the commonest inherited cardiac condition (prevalence, \(\sim 0.2\%\)).\(^1\) Symptoms arising from left ventricular (LV) outflow tract obstruction, present in \(\sim 30\%\) of HCM patients, are amenable to drug therapies and to interventions such as surgical septal myectomy or alcohol septal ablation.\(^2\) However, treatment options in symptomatic patients without outflow tract obstruction are substantially less successful, mandating a more comprehensive understanding of the mechanisms underlying symptoms in HCM with the intention of identifying and testing novel therapies.\(^3^4\)

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More than 400 mutations in genes encoding cardiac contractile proteins have been implicated in HCM.\(^5\) HCM-
causing mutations increase sarcomeric Ca²⁺ sensitivity, ATPase activity, and the energetic cost of myocyte contraction. These abnormalities led to the proposal that the pathophysiology of HCM is attributable, at least in part, to excessive sarcomeric energy use. The resulting hypertrophy of HCM, exacerbated by mitochondrial dysfunction and accompanied by microvascular dysfunction, may limit myocyte oxygen delivery and further exacerbate the primary energy deficiency. Consistent with a functional role for the observed energy deficiency of HCM, LV relaxation (a highly energy-requiring process) paradoxically slows in HCM patients on exercise and is correlated with exercise limitation. To assess a causative role for energy deficiency and to test a potentially novel therapeutic strategy for HCM, we evaluated whether perhexiline, an agent thought to improve cardiac energetics by shifting substrate use to more efficient carbohydrate metabolism, would increase exercise capacity by improving cardiac energetics and LV relaxation (ie, diastolic filling).

Methods
An expanded Methods section appears in the online-only Data Supplement.

Study Design
The study was approved by the South Birmingham Research Ethics Committee and conforms to the Declaration of Helsinki. All participants provided written informed consent. The study was a randomized, double-blind, placebo-controlled, parallel-group design of 3 to 6 months’ duration (mean, 4.6 ± 1.8 months). The predefined primary end point was peak oxygen consumption (peak V̇O₂); secondary end points were symptomatic status, resting myocardial energetics (ratio of phosphocreatine to adenosine triphosphate [PCr/ATP ratio]), and diastolic function at rest and during exercise (heart rate normalized time to peak filling [nTTPF]). A flow diagram of the study is shown in Figure 1.

Patient Selection
Patients were consecutively recruited from cardiomyopathy clinics at The Heart Hospital, University College London Hospitals (London,
UK) and Queen Elizabeth Hospital (Birmingham, UK) between 2006 and 2008. All patients fulfilled conventional echocardiographic criteria for the diagnosis of HCM (LV wall thickness, ≥1.5 cm in the absence of abnormal loading conditions).23,24 Exclusion criteria were as follows: 18 to 80 years of age, exertional symptoms, sinus rhythm, peak VO2 <75% of predicted for age and gender, and the absence of resting or provokable LV outflow tract obstruction (peak gradient <30 mm Hg). Exclusion criteria were the presence of epiperal coronary artery disease, abnormal liver function tests, concomitant use of amiodarone or selective serotonin reuptake inhibitors (because of potential drug interactions with perhexiline), and peripheral neuropathy; women of childbearing potential also were excluded. Diabetic patients were excluded to maintain the blinding of the study because perhexiline may lead to a reduction in plasma glucose, necessitating a reduction in antidiabetic therapy.

Control Selection
Thirty-three control subjects of similar age and gender distribution were recruited for comparison of baseline data. Control subjects were recruited via advertisements placed in the University Hospital of Birmingham, University of Birmingham, and local blood donor centers. Control subjects were asymptomatic and had normal ECGs/echocardiograms.

Intervention
After baseline studies, patients were randomized in a double-blind fashion, with a block size of 4, to receive either perhexiline 100 mg OD (n=24) or placebo (n=22). Serum perhexiline levels were obtained at 1 and 4 weeks after initiation of the drug. Dose adjustments were advised by an unblinded physician according to serum level to achieve therapeutic level (therapeutic range, 0.15 to 0.6 mg/L) and to avoid drug toxicity. Identical dosage adjustments were made for randomly allocated placebo-treated patients by the unblinded observer to ensure that blinding of the investigators was maintained as previously described.21

Statistical Analysis
Data were analyzed with SPSS 15.0 for Windows and Microsoft Office Excel 2007 and are expressed as mean±SEM. Comparisons of continuous variables between perhexiline and placebo baseline data were made by unpaired Student’s t test (2 tailed) if variables were normally distributed and the Mann–Whitney U test if the data were nonnormally distributed. Categorical variables were compared with the Pearson χ2 test. ANCOVA with baseline values as covariates was performed to test for the significance of differences in the perhexiline versus placebo group after treatment. A value of P<0.05 was taken to indicate statistical significance. For the primary end point of the overall study, 44 patients are required to detect a change in peak VO2 of 3 mL·kg⁻¹·min⁻¹ in the treatment versus the placebo group with a power of 90%, an SD of 3 mL·kg⁻¹·min⁻¹, and a value of P<0.05. Thirty patients are required to identify a 5% change in cardiac PCr/ATP ratio with a power of 90%, an SD of 4.1%, and a value of P<0.05. Forty patients are required to detect a change ≥25% in nTTPF with power of 0.99, an SD of 18%, and value of P<0.05.

Results
Baseline Data (HCM Patients Versus Control Subjects)
The clinical characteristics and cardiopulmonary exercise test results of the HCM patients and control subjects are shown in Table 1. The groups were similar with respect to age and gender. Heart rate was lower in the HCM group compared with the control subjects, probably because of medication use (β-blockers and/or calcium channel blockers).

Genomic DNA samples with consent for genetic analysis were available on 28 of the study HCM subjects. Thirteen subjects were found to have either known pathogenic variants or variants considered to be pathogenic on the basis of their absence in normal control chromosomes (n=1000) and predicted impact on protein structure. Three missense mutations were identified in MYH7 (1 previously reported and 2 novel); 9 pathogenic variants were identified in MYBPC3 (1 novel truncation, 6 previously reported missense mutations, and 2 novel missense mutations); and 1 previously reported missense mutation was identified in TNN1.

HCM patients exhibited marked exercise limitation compared with control subjects (peak VO2, 23±0.1 versus 38±0.2 mL·kg⁻¹·min⁻¹; P<0.0001; Table 1). This remained so after patients taking β-blockers were excluded (P<0.0001). Resting cardiac PCr/ATP ratio was lower in HCM patients than in control subjects (1.28±0.01 versus 2.26±0.02; P<0.0001; Table 1), and this remained so after the exclusion of patients taking β-blocker therapy (P<0.0001). At rest, nTTPF, a sensitive marker of LV relaxation, was similar in HCM patients and control subjects (0.17±0.002 versus 0.18±0.003 seconds; P=0.44). During submaximal exercise (at a workload that achieved 50% of heart rate reserve), it remained relatively constant in control subjects (from 0.18±0.003 to 0.16±0.002 seconds; δnTTPF=−0.01±0.004 seconds) but lengthened in patients (from 0.17±0.002 to 0.34±0.002 seconds; δnTTPF=0.13±0.003 seconds; P<0.0001; Table 1 and Figure 2). Transmirtal Doppler measurements showed no significant difference in peak E, deceleration time, and E/A ratio in HCM patients versus control subjects (Table 1). However, pulse-wave tissue Doppler measurements of S, E’, and A’ were significantly lower in HCM patients compared with control subjects (Table 1).

Randomized, Double-Blind, Placebo-Controlled, Parallel-Group Study
The perhexiline and placebo groups were well matched (Table 1). One patient (on placebo) did not complete the study because of poor compliance. Six patients were subtherapeutic and none were above the therapeutic range at the end of the study. Side effects were restricted to transient nausea (n=3) and dizziness (n=2) in the perhexiline group and transient nausea (n=2) in the placebo group. There were no instances of hepatotoxicity and no deaths or major adverse events during the study period.

Exercise Capacity (Peak Oxygen Consumption)
At baseline, peak VO2 was similar in both groups (Table 1). After treatment, peak VO2 fell by 1.3 mL·kg⁻¹·min⁻¹ in the placebo group (from 23.6±0.3 to 22.3±0.2 mL·kg⁻¹·min⁻¹) but increased by 2.1 mL·kg⁻¹·min⁻¹ in the perhexiline group (from 22.2±0.2 to 24.3±0.2 mL·kg⁻¹·min⁻¹; P=0.003; Table 2). There were no significant changes in VO2 anaerobic threshold or VE/VCO2 slope between the groups.

Symptomatic Status
Minnesota Living With Heart Failure Questionnaire score showed an improvement in the perhexiline group (from 36±0.94 to 28±0.75) but no change in the placebo group (from 37±1.21 to 34±1.25; P<0.001 for difference in
response between placebo and perhexiline). New York Heart Association classification improved in more patients in the perhexiline than the placebo group (67% versus 30%); fewer worsened (8% versus 20%; \( P<0.001 \)).

Myocardial Energetics
Typical cardiac \(^{31}\)P magnetic resonance spectroscopy spectra from a patient with HCM is shown in Figure 3. The mean Cramer-Rao ratios for PCr and ATP for the entire group were

### Table 1. Clinical Characteristics of HCM Patients and Control Subjects

<table>
<thead>
<tr>
<th></th>
<th>HCM Patients</th>
<th>Control Subjects</th>
<th>( P )</th>
<th>HCM (Perhexiline)</th>
<th>HCM (Placebo)</th>
<th>( P )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>55±0.26</td>
<td>52±0.46</td>
<td>0.2</td>
<td>56±0.46</td>
<td>54±0.64</td>
<td>0.42</td>
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<tr>
<td>Men, n (%)</td>
<td>46 (34)</td>
<td>33 (20)</td>
<td>0.64</td>
<td>24 (19)</td>
<td>22 (17)</td>
<td>0.69</td>
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<tr>
<td>Heart rate, bpm</td>
<td>69±0.27</td>
<td>82±0.47</td>
<td>&lt;0.001*</td>
<td>69±0.53</td>
<td>69±0.52</td>
<td>0.97</td>
</tr>
<tr>
<td>Systolic BP, mm Hg</td>
<td>126±0.64</td>
<td>126±0.44</td>
<td>0.93</td>
<td>123±0.84</td>
<td>130±0.92</td>
<td>0.2</td>
</tr>
<tr>
<td>Diastolic BP, mm Hg</td>
<td>76±0.25</td>
<td>78±0.34</td>
<td>0.33</td>
<td>74±0.45</td>
<td>78±0.57</td>
<td>0.24</td>
</tr>
<tr>
<td>Peak ( V_{02} ), mL·kg(^{-1})·min(^{-1})</td>
<td>23±0.1</td>
<td>38±0.2</td>
<td>&lt;0.0001*</td>
<td>22.2±0.2</td>
<td>23.6±0.3</td>
<td>0.42</td>
</tr>
<tr>
<td>Resting nTTPF, s</td>
<td>0.17±0.002</td>
<td>0.18±0.003</td>
<td>0.44</td>
<td>0.19±0.003</td>
<td>0.17±0.004</td>
<td>0.52</td>
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<tr>
<td>PCr/ATP ratio</td>
<td>1.28±0.01</td>
<td>2.26±0.02</td>
<td>&lt;0.0001*</td>
<td>1.27±0.02</td>
<td>1.29±0.01</td>
<td>0.86</td>
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</tbody>
</table>

**Echocardiography**

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>LVEF, %</td>
<td>65±0.2</td>
<td>63±0.2</td>
<td>0.24</td>
<td>66±0.35</td>
<td>63±0.34</td>
<td>0.24</td>
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<tr>
<td>LVEDV index, mL/m(^2)</td>
<td>46±0.26</td>
<td>41±0.4</td>
<td>0.1</td>
<td>44±0.58</td>
<td>44±0.31</td>
<td>0.32</td>
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<tr>
<td>LVESV index, mL/m(^2)</td>
<td>16±0.15</td>
<td>15±0.14</td>
<td>0.26</td>
<td>15±0.28</td>
<td>16±0.16</td>
<td>0.18</td>
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<tr>
<td>LAV index, mL/m(^2)</td>
<td>35.37±0.33</td>
<td>14.68±0.39</td>
<td>&lt;0.0001*</td>
<td>35.9±0.38</td>
<td>39.45±0.77</td>
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<tr>
<td>Mitral E velocity, m/s</td>
<td>0.69±0.003</td>
<td>0.66±0.005</td>
<td>0.33</td>
<td>0.66±0.01</td>
<td>0.67±0.004</td>
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<tr>
<td>Mitral A velocity, m/s</td>
<td>0.7±0.005</td>
<td>0.59±0.004</td>
<td>0.01*</td>
<td>0.76±0.01</td>
<td>0.68±0.01</td>
<td>0.13</td>
</tr>
<tr>
<td>Mitral E/A ratio</td>
<td>1.1±0.01</td>
<td>1.17±0.01</td>
<td>0.28</td>
<td>1±0.01</td>
<td>1.03±0.01</td>
<td>0.1</td>
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<tr>
<td>Mitral DCT, ms</td>
<td>238±1.66</td>
<td>259±2.14</td>
<td>0.26</td>
<td>246±2.39</td>
<td>227±1.86</td>
<td>0.52</td>
</tr>
<tr>
<td>TDI S velocity, cm/s</td>
<td>0.06±0.001</td>
<td>0.08±0.001</td>
<td>&lt;0.0001*</td>
<td>0.06±0.001</td>
<td>0.06±0.001</td>
<td>0.65</td>
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<tr>
<td>TDI E' velocity, cm/s</td>
<td>0.06±0.001</td>
<td>0.09±0.001</td>
<td>0.02*</td>
<td>0.06±0.001</td>
<td>0.06±0.001</td>
<td>0.6</td>
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<tr>
<td>TDI A' velocity, m/s</td>
<td>0.07±0.001</td>
<td>0.09±0.001</td>
<td>&lt;0.0001*</td>
<td>0.07±0.001</td>
<td>0.06±0.001</td>
<td>0.62</td>
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<tr>
<td>E/E' ratio</td>
<td>12±0.1</td>
<td>8±0.1</td>
<td>&lt;0.0001*</td>
<td>12±0.2</td>
<td>12±0.1</td>
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<tr>
<td>MWT [cm]</td>
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<td>...</td>
<td>...</td>
<td>2.32±0.02</td>
<td>2.25±0.01</td>
<td>0.58</td>
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<tr>
<td>F H/O HCM, n</td>
<td>19</td>
<td>0</td>
<td>...</td>
<td>11</td>
<td>8</td>
<td>0.51</td>
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<tr>
<td>F H/O SCD, n</td>
<td>9</td>
<td>0</td>
<td>...</td>
<td>4</td>
<td>5</td>
<td>0.52</td>
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<tr>
<td>Drug therapy, n</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>( \beta )-blocker</td>
<td>17</td>
<td>0</td>
<td>...</td>
<td>10</td>
<td>7</td>
<td>0.21</td>
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<tr>
<td>Calcium channel block</td>
<td>24</td>
<td>0</td>
<td>...</td>
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<td>8</td>
<td>0.53</td>
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<tr>
<td>Diuretic</td>
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<td>...</td>
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<tr>
<td>ACE inhibitor</td>
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<td>0</td>
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<td>3</td>
<td>2</td>
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<tr>
<td>ARB</td>
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<td>...</td>
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<td>Warfarin</td>
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<td>Statin</td>
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<td>...</td>
<td>7</td>
<td>7</td>
<td>0.9</td>
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</tbody>
</table>

**BP** indicates blood pressure; LVEF, LV ejection fraction; LVEDV index, LV end-diastolic volume indexed to body surface area; LVESV, LV end-systolic volume indexed to body surface area; LAV, left atrial volume; DCT, deceleration time; TDI, tissue Doppler imaging; MWT, minimal wall thickness; F H/O, family history of; SCD, sudden cardiac death; ACE, angiotensin-converting enzyme; and ARB, angiotensin II receptor blockers. TDI measurements were averaged from basal anterolateral and basal inferoseptum in apical 4-chamber view.
7.5% and 10.8%, respectively, indicating satisfactory signal-to-noise ratio. Three patients were excluded from the initial analysis because of poor signal-to-noise ratio (Cramer-Rao ratios >20%). The PCr/ATP ratio increased with perhexiline (1.27±0.02 to 1.73±0.02) compared with placebo (1.29±0.01 to 1.23±0.01; P=0.003; Table 2). The effect of perhexiline on PCr/ATP ratio remained significant with the inclusion of the 3 patients with poor signal-to-noise ratio (P=0.02).

**Serum Metabolite Profiles**

Perhexiline induced significant changes in serum glucose (5.39±0.14 to 4.96±0.20 mmol/L, P=0.003, versus 5.36±0.26 to 5.32±0.19 mmol/L, P=0.7) and free fatty acid levels (381.61±33.56 to 297.39±31.00 mmol/L, P=0.04, versus 353.11±34.74 to 329.00±32.62 mmol/L, P=0.61) in the perhexiline versus placebo groups, respectively (Table 3).

**Exercise Radionuclide Measurements**

Whereas the placebo group showed prolongation of nTTPF during exercise before and after therapy (by 0.15±0.007 and 0.11±0.008 seconds, respectively), in the perhexiline group, nTTPF lengthened at baseline (by 0.11±0.008 seconds) but shortened on treatment (by −0.01±0.005 seconds; P=0.03 for difference between the perhexiline and placebo response; Figure 2A and 2B). There were no significant changes in ejection fraction at rest or during exercise (Table 2). Ejection fraction decreased <50% on exercise in 3 patients (2 in the perhexiline group and 1 in the placebo group).

Although our study was not designed (and hence not powered) to relate genetic status to drug response, there was no statistical heterogeneity in baseline characteristics or response to therapy as judged from the perspective of genotype status (data not shown).

**Discussion**

This study confirms that patients with symptomatic nonobstructive HCM manifest a cardiac energy defect (reduced PCr/ATP ratio) accompanied by a slowing of the energy-dependent early diastolic LV active relaxation during exercise (prolongation of nTTPF). Consistent with the hypothesis that impaired myocardial energy status contributes to the pathophysiology of HCM, perhexiline augmented myocardial PCr/ATP ratio, corrected the abnormal prolongation of nTTPF on

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**Table 2. Effects of Placebo and Perhexiline on Metabolic Exercise Parameters, Myocardial Energetic, Symptomatic Status, and LV Systolic Function at Rest and During Exercise**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Metabolic exercise parameters</th>
<th>Perhexiline Group</th>
<th>Placebo Group</th>
<th>P, ANCOVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline</td>
<td>Follow-Up</td>
<td>Baseline</td>
<td>Follow-Up</td>
</tr>
<tr>
<td>Peak VO₂, mL · kg⁻¹ · min⁻¹</td>
<td>22.2±0.2</td>
<td>24.3±0.2</td>
<td>23.6±0.3</td>
<td>22.3±0.2</td>
</tr>
<tr>
<td>VO₂-AT, mL · kg⁻¹ · min⁻¹</td>
<td>16±0.11</td>
<td>15±0.1</td>
<td>17±0.23</td>
<td>16±0.15</td>
</tr>
<tr>
<td>Ve/VCO₂ slope</td>
<td>30±0.12</td>
<td>32±0.12</td>
<td>30±0.23</td>
<td>32±0.3</td>
</tr>
<tr>
<td>Myocardial energetic status</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCr/ATP ratio</td>
<td>1.27±0.02</td>
<td>1.73±0.02</td>
<td>1.29±0.01</td>
<td>1.23±0.01</td>
</tr>
<tr>
<td>Symptomatic status</td>
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<tr>
<td>MLHFQ score</td>
<td>36±0.94</td>
<td>28±0.75</td>
<td>37±1.21</td>
<td>34±1.25</td>
</tr>
<tr>
<td>LV systolic function (at rest and during exercise), %†</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resting EF</td>
<td>68±0.51</td>
<td>67±0.49</td>
<td>66±0.46</td>
<td>65±0.42</td>
</tr>
<tr>
<td>Exercise EF</td>
<td>72±0.75</td>
<td>69±0.45</td>
<td>73±0.56</td>
<td>75±0.39</td>
</tr>
</tbody>
</table>

AT indicates anaerobic threshold; Ve/VCO₂ slope, minute ventilation–carbon dioxide production relationship; MLHFQ, Minnesota Living With Heart Failure Questionnaire; and EF, ejection fraction. ANCOVA P values represent the significant difference between perhexiline and placebo responses.

*Statistically significant.
†Measured with radionuclide ventriculography.
perhexiline are likely to be complex, its capacity to divert myocardial metabolism toward carbohydrates, especially in the context of myocardial oxygen limitation (eg, resulting from microvascular dysfunction),12,14 is predicted to enhance the efficiency of myocardial energy generation.22,36,37 Exploring this effect, there is evidence that agents modifying substrate use (eg, trimetazidine and perhexiline) enhance myocardial energetics and are efficacious in the energy-starved state of heart failure.21,32,38 The corresponding improvements in symptoms (the principal feature of HCM in these patients) and in peak VO\textsubscript{2} (≈2 mL·kg\textsuperscript{-1}·min\textsuperscript{-1} absolute, 3.3 mL·kg\textsuperscript{-1}·min\textsuperscript{-1} placebo corrected) with perhexiline are clinically meaningful, and to the best of our knowledge, improvements of this magnitude have not been reported for other therapies in nonobstructive HCM. To put these benefits into context, they are comparable to the benefits noted with gradient reduction in obstructive HCM (≈3 mL·kg\textsuperscript{-1}·min\textsuperscript{-1}).39,40 Importantly, this encouraging efficacy was achieved with few side effects; perhexiline plasma monitoring and dose titration prevent the hepatotoxicity and neuropathy that may occur in slow drug metabolizers.22

When genetic analysis was possible, the proportion (46%) and range of sarcomeric mutations were typical of other HCM cohorts. Although our study was not designed to relate genetic status to drug response, our patients (regardless of mutation status) responded to perhexiline. Sarcomeric mutations, by virtue of their well-characterized energy-profligate biophysical properties, provide a mechanistic rationale to treat HCM with energy-modulating therapies. Our data extend this argument by suggesting that, regardless of mutation status, the energy deficiency that characterizes HCM and its physiological sequelae renders most HCM patients amenable to metabolic therapy.

In this study, perhexiline (or placebo) was added to standard medical therapy. Such therapy (eg, β-blockers) might have affected the cardiovascular response of participants to exercise. To account for this potential confounder, all pertinent physiological parameters were corrected for heart rate. In addition, the statistical significance of the results remained unchanged regardless of whether patients on β-blockers were included or excluded from analysis. Similarly, patients with flow-limiting coronary disease and diabetes mellitus were excluded to avoid the confounding influence of impaired cardiac energetic status associated with these disorders.41 Multiple objective and independent parameters (ie, PCr/ATP, nTTPF, and VO\textsubscript{2}) were assessed to obviate the biases that may confound interpretation of phase 2 trials. The PCr/ATP ratio was measured at rest; we speculate that the impact of perhexiline on PCr/ATP would be more striking in exercise, but current technology does not permit dynamic magnetic resonance spectroscopy measurements. To substantiate the 31P magnetic resonance spectroscopy findings, analyses were performed both including and excluding studies with unacceptable signal-to-noise ratios (Cramer-Rao >20%); the results remained statistically similar under both circumstances. Although we do not present definitive evidence that perhexiline shifts myocardial substrate use toward carbohydrate metabolism, the combination of extensive biochemical evidence of the capacity of perhexi-

### Table 3. The Impact of Perhexiline and Placebo on Serum Metabolites in HCM Patients. HOMA, Homeostasis Model of Assessment. Data Are Presented as Mean±SEM

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Perhexiline Group</th>
<th>Placebo Group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline Follow-Up</td>
<td>Baseline Follow-Up</td>
</tr>
<tr>
<td>Free fatty acids [μmol/L]</td>
<td>382±34 297±31*</td>
<td>353±35 329±33</td>
</tr>
<tr>
<td>Glucose [mmol/L]</td>
<td>5.39±0.14 4.96±0.2**</td>
<td>5.36±0.26 5.32±0.19</td>
</tr>
<tr>
<td>Insulin [mU/L]</td>
<td>16.3±4.8 10.2±1.6</td>
<td>10.9±2.1 7.9±1.3</td>
</tr>
<tr>
<td>Insulin resistance [HOMA index]</td>
<td>0.32±0.1 0.19±0.03</td>
<td>0.22±0.05 0.16±0.03</td>
</tr>
<tr>
<td>GLYCEROL [μmol/L]</td>
<td>96±11 107±8</td>
<td>83±8.06 106±12</td>
</tr>
</tbody>
</table>

*P<0.05 vs baseline. **P<0.005 vs baseline.

exercise, improved symptoms, and increased the functional capacity of patients in the perhexiline group.

The observation that patients with HCM manifest impaired myocardial PCr/ATP (Table 1), at least those with sarcomeric mutations, is an expected and likely direct consequence of the biophysical properties of the mutations and accords with previous animal and human studies.16,17,25–27 Thus, although the pathogenesis of sarcomeric HCM has been varyingly attributed to increased sarcomeric Ca\textsuperscript{2+} sensitivity, ATPase activity, and aberrant cross-bridge dynamics6,8 with complications such as oxidative stress28 and altered sarcomeric phosphorylation,29,30 a common feature of such studies is the excessive energetic cost of tension generation by sarcomeric mutations.7,9 In addition to these biophysical considerations, further evidence that the energy deficiency in HCM is a primary event and not a secondary feature of cardiac remodeling (either LV hypertrophy or heart failure) derives from the observation that myocardial high-energy phosphates are even compromised in asymptomatic HCM16 and prehypertrophic cardiomyopathy.10,17 The resulting final common path of the energy deficiency, rather than sarcomeric mutations per se, may specifically contribute to the HCM phenotype, as seen in other primary disorders of myocardial energy deficiency (eg, mitochondrial disorders and Friedreich ataxia).31

Because the heart has a high energy requirement,32 cardiac energy deficiency would be expected to translate into characteristic physiological defects such as slowing of energy-dependent33 early diastolic relaxation. Thus, although the nTTPF in control subjects remained approximately constant between rest and exercise, nTTPF paradoxically lengthened in HCM patients (Figure 2). This slower filling in the context of the reduced diastolic filling time reduces cardiac output and limits exercise capacity.18

It has been proposed that perhexiline inhibits the metabolism of free fatty acids and thereby enhances myocardial carbohydrate use (in effect improving insulin resistance34) by suppressing carnitine palmitoyl transferase I and II, transporters that are crucial for the uptake of long-chain free fatty acids into mitochondria.19,20,35 The present study supports this proposal by observing that perhexiline, in common with other metabolic modulators,36 improved the systemic metabolic milieu by significantly decreasing serum glucose and free fatty acids. Thus, although the mechanisms of action of
line to inhibit carnitine palmitoyl transferase and our demonstration of consistent changes in serum free fatty acids and glucose supports the hypothesis that perhexiline augments myocardial PCr/ATP, at least in part through metabolic modulation.

Conclusions

The present study supports the hypothesis that HCM is, at least in part, a disease of energy deficiency. Metabolic modulation, myocardial PCr/ATP augmentation, and normalized diastolic ventricular filling by perhexiline translated into significant and clinically meaningful subjective and objective clinical improvement in patients with symptomatic nonobstructive HCM. Thus, this proof-of-concept study suggests that perhexiline has the capacity to make substantial impacts on the quality of life of this highly symptomatic population for whom alternative evidence-based therapeutic strategies are limited. We propose that longer-term studies are now needed to evaluate the impact of metabolic modulation both for symptom control and as potentially disease-modifying therapy that may improve prognosis and/or lead to LV hypertrophy regression in HCM.

Acknowledgments

We thank Dr Alan Hutchins for the perhexiline assays and for his independent supervision of dosage adjustments. We also thank Peter Nightingale for his assistance with statistical analysis.

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Disclosures

Drs Ashrafian and Frenneaux have successfully applied for method-of-use patents for the use of perhexiline in heart failure and cardiomyopathies. The other authors report no conflicts.

References

25. Deleted in proof.
26. Spindler M, Snape KW, Christe ME, Sweeney HL, Seidman CE, Seidman JG, Ingwall JS. Diastolic dysfunction and altered energetics in the alpha-
Cardiac energy impairment is a consistent feature of hypertrophic cardiomyopathy and precedes the development of a hypertrophic phenotype. We hypothesized that this energy deficiency plays a key role in the pathophysiology of exercise limitation via impairment of the highly energy-dependent process of left ventricular active relaxation on exercise. To test this hypothesis, we assessed whether the metabolic modulator perhexiline augmented myocardial energetics in hypertrophic cardiomyopathy and whether this translated into improved physiological and clinical outcomes in a randomized, double-blind, placebo-controlled study. In accordance with previous studies, the hypertrophic cardiomyopathy patients in the present study, who were symptomatic but manifested no left ventricular outflow tract obstruction, had a significantly decreased myocardial energy charge as assessed by $^3$P magnetic resonance spectroscopy; this was accompanied by a paradoxical dynamic slowing of myocardial relaxation during exercise. Perhexiline improved myocardial energetics, normalized the impairment of dynamic myocardial relaxation, and improved both patient symptoms and exercise capacity. The results of the present study support the hypothesis that energy deficiency contributes to the pathophysiology of exercise limitation in hypertrophic cardiomyopathy and that augmenting myocardial energetics through metabolic modulation may be a novel and potentially effective therapy for the management of symptomatic hypertrophic cardiomyopathy in patients without left ventricular outflow tract obstruction, although this requires confirmation in a larger study. The therapeutic potential is especially important in this group of patients in whom treatment options are limited.
Metabolic Modulator Perhexiline Corrects Energy Deficiency and Improves Exercise Capacity in Symptomatic Hypertrophic Cardiomyopathy

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Cardiopulmonary Exercise Test

All study participants underwent symptom-limited erect treadmill exercise testing (Schiller CS-200 Ergo-Spiro exercise machine) using a standard ramp protocol with simultaneous respiratory gas analysis. Peak oxygen consumption (peak VO$_2$) was defined as the highest peak VO$_2$ achieved during exercise (with RER >1) expressed in ml/min/kg. Predicted % peak VO$_2$ for age and gender was calculated as per established guidelines. We also measured minute ventilation – carbon dioxide production relationship (VE/VCO$_2$ slope) and VO$_2$ at anaerobic threshold (AT) as previously described.

Symptomatic status assessment

Symptom status was determined by a single investigator (KA) using the NYHA functional classification. All patients completed a Minnesota Living with heart failure questionnaire at baseline and at the end of the treatment phase.

Transthoracic Echocardiography

Echocardiography was performed with participants in the left lateral decubitus position with a Vivid 7 echocardiographic machine (GE Healthcare) and a 2.5-MHz transducer. LVEF was derived from a modified Simpson’s formula. LA volume index and maximal wall thickness were measured. Pulse and continuous wave Doppler were used to assess resting LVOTO gradient and trans-mitral Doppler parameters. Mitral annulus velocities (pulse wave Tissue Doppler imaging [PW-TDI]) were recorded and averaged from basal anterolateral and basal inferoseptum in apical 4-chamber view.
Radionuclide Ventriculography

Diastolic filling was assessed by equilibrium R-wave gated blood pool scintigraphy at rest and during graded semi-erect exercise on a cycle ergometer as previously described.\textsuperscript{5,6} LVEF, peak left ventricular filling (end-diastolic count per second (EDC/s)) and time to peak filling normalised for R-R interval (nTTPF), an indirect measure of the rate of LV active relaxation were assessed at rest and during exercise (50\% of heart rate reserve). The validity of these radionuclide measures of diastolic filling at high heart rates has been established previously.\textsuperscript{5,6}

Myocardial energetics

In vivo myocardial energetics were measured using a \textsuperscript{31}P Cardiac MRS at 3-Tesla Phillips Achieva 3T scanner, as previously validated.\textsuperscript{7} A Java magnetic resonance user interface v3.0 (jMRUI) was used for analysis.\textsuperscript{8} PCr and γ-ATP peaks were used to determine the PCr/ATP ratio which is a measure of the cardiac energetic state. Data were analyzed by an investigator who was blinded to the participants’ clinical status. Cramér–Rao ratios were used to assess signal:noise ratio (SNR).\textsuperscript{7}

Serum metabolites profiles

The following analytical measurements were carried out; blood glucose, FFA, insulin, insulin resistance (HOMA index) and plasma glycerol as previously described.\textsuperscript{9}

Genetic Analysis

Mutational analysis was performed on genomic DNA by direct sequencing to include the complete coding sequence and flanking regions of all of the genes encoding sarcomeric
proteins that have been shown to be mutated in HCM (MYH7, MYBPC3, TNNT2, TNNI3, TPN1, MYL2, MYL3, ACTC1). In addition PRKAG2 and LAMP2 were screened to exclude phenocopies.
Reference List


