The spectrum of exercise tolerance in mitochondrial myopathies: a study of 40 patients

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Summary
Impaired skeletal muscle oxidative phosphorylation in patients with severe mitochondrial respiratory chain defects results in disabling exercise intolerance that is associated with a markedly blunted capacity of muscle to increase oxygen utilization in relation to circulatory and ventilatory responses that increase oxygen delivery to muscle during exercise. The range of oxidative limitation and the relationship between the severity of oxidative defects and physiological responses to exercise among a broader spectrum of mitochondrial respiratory chain defects has not been defined. We evaluated oxidative capacity and circulatory and ventilatory responses to maximal cycle exercise in 40 patients with biochemically and/or molecularly defined mitochondrial myopathy (MM) associated with varying levels of exercise tolerance, and compared responses with those in healthy sedentary individuals. In the MM patients, mean peak work capacity (0.88 ± 0.6 W/kg) and oxygen uptake (VO2, 16 ± 8 ml/kg/min) were significantly lower (P < 0.01) than in controls (mean work capacity = 2.2 ± 0.7 W/kg; VO2 = 32 ± 7 ml/kg/min), but the patient range was broad (0.17–3.2 W/kg; 6–47 ml/kg/min). Oxidative capacity in patients was limited by the ability of muscle to extract available oxygen from blood [mean peak systemic arteriovenous O2 difference (a–vO2); patients = 7.7 ± 3.5, range 2.7–17.6 ml/dl, controls = 15.2 ± 2.1 ml/dl], as indicated by a linear correlation between peak VO2 and peak systemic a–vO2 difference (r² = 0.69). In the patients, the increase in cardiac output relative to VO2 (mean ΔQ/ΔVO2 = 15.0 ± 13.6; range 3.3–73) and ventilation (mean peak VE/VO2 = 65 ± 24; range 21–104) were exaggerated compared with controls (mean ΔQ/ΔVO2 = 5.1 ± 0.7; VE/VO2 = 41.2 ± 7.4, P < 0.01). There was a negative exponential relationship between ΔQ/ΔVO2 and peak systemic a–vO2 difference (r² = 0.92) and between peak VE/VO2 and systemic a–vO2 difference (r² = 0.53). In patients with heteroplasmic mtDNA mutations, we found an inverse relationship between the proportion of skeletal muscle mutant mtDNA and peak extraction of available oxygen during exercise (r² = 0.70). We conclude that the degree of exercise intolerance in MM correlates directly with the severity of impaired muscle oxidative phosphorylation as indicated by the peak capacity for muscle oxygen extraction. Exaggerated circulatory and ventilatory responses to exercise are direct consequences of the level of impaired muscle oxidative phosphorylation and increase exponentially in relation to an increasing severity of oxidative impairment. In patients with mtDNA mutations, muscle mutation load governs mitochondrial capacity for oxidative phosphorylation and determines exercise capacity.

Keywords: mitochondrial myopathies; exercise; oxidative metabolism

Abbreviations: MET = metabolic equivalent; MM = mitochondrial myopathy; RER = respiratory exchange ratio
Introduction
Exercise intolerance is a well-recognized clinical feature of mitochondrial respiratory chain defects due to pathogenic mutations of mitochondrial or nuclear DNA. Severely impaired muscle oxidative phosphorylation results in disabling exercise limitations in which trivial exertion produces muscle fatigue and lactic acidosis. In such patients, low levels of exercise cause prominent tachycardia and dyspnea due to increases in cardiac output and ventilation that exceed the capacity of skeletal muscle to utilize the increase in oxygen delivery mediated by these physiological responses (Haller and Bertocci, 1994).

This pattern of exercise pathophysiology in mitochondrial myopathies has been defined in case reports or small series which are probably skewed to the most severe examples of oxidative limitations (Carroll et al., 1979; Elliot et al., 1989; Haller et al., 1989, 1991; Vissing et al., 1996; Taivassalo et al., 2001). Clinical, biochemical and molecular studies suggest that the range of oxidative impairment in mitochondrial myopathies (MMs), especially those attributable to heteroplasmic mtDNA mutations, is broad. However, detailed assessment of exercise and oxidative capacity and of the physiological components of oxygen utilization in a broad range of MM patients has not been undertaken heretofore. Accordingly, we have evaluated exercise and oxidative capacities as well as circulatory and ventilatory responses to exercise in 40 patients with biochemically and/or molecularly defined MMs. The primary objectives were to define the spectrum of exercise capability in this patient population and to illuminate the relationship between molecular and cellular features of respiratory chain defects and cardiopulmonary responses to exercise that normally are closely linked to muscle oxygen utilization.

Methods
Subjects
Forty patients (22 females, 18 males; 37 ± 12 years) with heterogeneous clinical, biochemical and molecular features of MM associated with electron transport chain defects were evaluated (Table 1). Clinically, patients had varying levels of exercise tolerance ranging from severe fatigue, weakness and occasional aching of active muscles with a rapid heartbeat and a sense of breathlessness provoked by trivial exercise, to no apparent exercise limitation. There was no evidence of a cardiomyopathy or impaired cardiac conduction in any patient. The range of clinical symptoms is summarized in Table 1. Thirty of the 40 patients had defined mtDNA mutations. In 23 of these 30 patients, the mtDNA mutation loads, defined as the percentage of mutant relative to total mtDNA in skeletal muscle, was quantified. In cases where the molecular mutation has not yet been identified, biochemical and histochemical features in the muscle biopsy were indicative of either a mitochondrial or nuclear-encoded gene mutation (Table 1). A group of 32 healthy sedentary individuals (nine females, 23 males, 39 ± 8 years) were used as controls for comparison of exercise responses.

The experimental protocol was approved by the Institutional Review Board of the University of Texas Southwestern Medical Center and Presbyterian Hospital of Dallas as well as the ethics committee of the Copenhagen Muscle Research Center, Denmark. Informed consent to participate was obtained from each patient.

Physiological exercise testing
All individuals were familiarized with the experimental set-up prior to testing. Gas exchange and cardiac output determinations were performed at rest and during an incremental workload exercise test on an electronically braked, pedal rate-independent cycle ergometer (MedGraphics 2000) in which the workload increased 5 or 10 W every 1–2 min. The total duration of the cycle test typically was 10–15 min, and ended when the individual reached maximal heart rate (220 – age) or exhaustion, as indicated by maximal levels of self-perceived exertion using the validated Borg Scale (Borg, 1982).

Expired air was collected in Douglas bags for 120 s at rest, and for 60 s at submaximal workloads and at peak exercise workloads. The fractions of O2, CO2 and N2 in each bag were analysed in a Marquette 1100 Medical Gas Analyzer. Respiratory minute volume was measured with a balanced Tissot spirometer, allowing for determination of oxygen uptake (VO2), carbon dioxide production (VCO2), the respiratory exchange ratio (RER, i.e. VCO2/VO2), ventilation (VE) and the ventilatory equivalent for oxygen (VE/VO2). Cardiac output (Q) was measured non-invasively utilizing acetylene rebreathing in which the rate of disappearance of C2H2 from a rebreathing bag is proportional to pulmonary blood flow and cardiac output (Triebwasser et al., 1977). As indicated by the Fick equation, VO2 is the product of Q and oxygen extraction [systemic arteriovenous oxygen difference (a–vO2)]. Accordingly, the measurement of VO2 and Q allows for calculation of a–vO2 difference, thus providing an estimate of muscle oxygen extraction (Mitchell and Blomqvist, 1971).

The final workload (peak W/kg) achieved by patients was considered their peak work capacity. Peak oxygen consumption (VO2max) denotes cardiovascular or ‘aerobic fitness’. It reflects both Q, i.e. peak capacity of the heart to pump oxygen and blood to skeletal muscle, and the capacity of muscle to extract available oxygen from blood (a–vO2 difference). Cardiac output and, to a lesser extent, ventilation normally are closely coupled to increases in muscle oxygen utilization during exercise, irrespective of age, sex, body weight or level of conditioning (Wasserman and Whipp, 1975; Faulkner et al., 1977). For each subject, the increase in cardiac output relative to the increase in oxygen utilization (ΔQ/ΔVO2) was calculated from the slope of the linear regression between cardiac output (Q; l/min) and oxygen utilization (VO2; l/min) from rest, submaximal and maximal exercise data. In healthy
individuals, cardiac output increases ~5 l for each litre of increase in oxygen consumption. Since arterial blood norm-
ally contains ~200 ml O$_2$/l, a $DQ/DVO_2$ of 5 indicates a virtual 1:1 relationship between oxygen delivery and oxygen utilization during exercise. Oxidative limitation due to deconditioning maintains a $DQ/DVO_2$ @ 5. In contrast, when $VO_2$ is limited by impaired muscle oxidative phosphorylation, the normal coupling between O$_2$ delivery and utilization is disrupted and $DQ/DVO_2$ >> 5 (Haller and Bertocci, 1994). VE/$VO_2$ is a more complex relationship, with VE linearly related to $VO_2$ at moderate workloads but rising disproportionately to $VO_2$ above the so-called ‘anaerobic’ threshold (Wasserman, 1986).

Heart rate was monitored continuously during rest and exercise with a 12-lead ECG (Quinton 3040 ECG monitor). All subjects had intravenous catheters inserted in a cubital vein from which blood was drawn for lactate analysis at rest, at various submaximal exercise levels and at the maximal workload. Whole blood samples were assayed using a commercially available analyser (Yellow Springs Instruments).

### Table 1 Mitochondrial myopathy patient characteristics

<table>
<thead>
<tr>
<th>Patient</th>
<th>Sex</th>
<th>Age (years)</th>
<th>Other clinical features</th>
<th>Nature of mutation</th>
<th>Genome</th>
<th>Mutation load</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. JL M</td>
<td>24</td>
<td>CPEO</td>
<td>5 kb deletion</td>
<td>mtDNA</td>
<td>29%</td>
<td></td>
</tr>
<tr>
<td>2. SL F</td>
<td>39</td>
<td>CPEO</td>
<td>Single deletion</td>
<td>mtDNA</td>
<td>37%</td>
<td></td>
</tr>
<tr>
<td>3. JF M</td>
<td>38</td>
<td>CPEO</td>
<td>Single deletion</td>
<td>mtDNA</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>4. LJM</td>
<td>37</td>
<td>CPEO</td>
<td>6 kb deletion</td>
<td>mtDNA</td>
<td>45%</td>
<td></td>
</tr>
<tr>
<td>5. LJ F</td>
<td>48</td>
<td>CPEO</td>
<td>1 kb deletion</td>
<td>mtDNA</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>6. CP F</td>
<td>57</td>
<td>CPEO</td>
<td>Single deletion</td>
<td>mtDNA</td>
<td>53%</td>
<td></td>
</tr>
<tr>
<td>7. UI F</td>
<td>53</td>
<td>CPEO</td>
<td>5 kb deletion</td>
<td>mtDNA</td>
<td>63%</td>
<td></td>
</tr>
<tr>
<td>8. LJM</td>
<td>67</td>
<td>CPEO</td>
<td>1 kb deletion</td>
<td>mtDNA</td>
<td>67%</td>
<td></td>
</tr>
<tr>
<td>9. TK F</td>
<td>30</td>
<td>CPEO</td>
<td>4.3 kb deletion</td>
<td>mtDNA</td>
<td>78%</td>
<td></td>
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<tr>
<td>10. RJ F</td>
<td>30</td>
<td>CPEO</td>
<td>5 kb deletion</td>
<td>mtDNA</td>
<td>78%</td>
<td></td>
</tr>
<tr>
<td>11. PB F</td>
<td>43</td>
<td>CPEO</td>
<td>Single deletion</td>
<td>mtDNA</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td>12. PS F</td>
<td>38</td>
<td>Myalgia</td>
<td>tRNAglu G14710A</td>
<td>mtDNA</td>
<td>67%</td>
<td></td>
</tr>
<tr>
<td>13. WB M</td>
<td>53</td>
<td>Pure EI</td>
<td>tRNAtrp T5543C</td>
<td>mtDNA</td>
<td>95%</td>
<td></td>
</tr>
<tr>
<td>14. PL F</td>
<td>35</td>
<td>MELAS</td>
<td>tRNAleu 3243</td>
<td>mtDNA</td>
<td>83%</td>
<td></td>
</tr>
<tr>
<td>15. RH F</td>
<td>29</td>
<td>Ataxia, hearing loss, epilepsy</td>
<td>A3243G</td>
<td>mtDNA</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td>16. SF M</td>
<td>46</td>
<td>Diabetes mellitus, hearing loss, migraine</td>
<td>A3243G</td>
<td>mtDNA</td>
<td>89%</td>
<td></td>
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</tbody>
</table>

Pure EI = pure exercise intolerance with no other signs or symptoms of mitochondrial disease; CPEO = chronic progressive external ophthalmoplegia; Cytb = cytochrome b; MELAS = mitochondrial encephalomyopathy, lactic acidosis and strokes; MERRF = myoclonus epilepsy with ragged red fibres; mtDNA = mitochondrial DNA; nDNA = nuclear DNA; * = suspected, ? = unknown.

Exercise in mitochondrial myopathy
patient and control group means when assumptions of normality and equal variances were met. In comparisons where data were not normally distributed and variances were not equal (peak VO2, ΔQ/ΔVO2 and VE/VO2), the Mann–Whitney rank sum test was applied to determine differences in median values between the two groups. Differences were considered statistically significant when P < 0.05. To determine the strength of the relationship between variables, regression analysis was performed on data from MM patients.

Results
The average weight of MM patients was lower than controls (64.4 ± 19 versus 78.5 ± 14 kg, P < 0.01). Indices reflecting oxidative capacity are therefore normalized to body weight.

Physiology at rest
Resting oxygen consumption was similar in both the MM patients and control subjects (MM group = 4.0 ± 0.9; control = 3.7 ± 0.8 ml/kg/min). Cardiac output was slightly higher in the patient group (MM = 88.0 ± 22; control = 66.0 ± 20 ml/kg/min, P < 0.01) and systemic a–vO2 difference was slightly lower (MM = 4.8 ± 1.3; controls = 5.5 ± 1.4 ml/dl, P < 0.05). Resting ventilation (MM = 172.4 ± 65; control = 146.2 ± 50 ml/kg/min), RER (MM = 0.82 ± 0.1; control 0.85 ± 0.1) and heart rate (MM = 79 ± 15; control = 75 ± 15) did not differ between the two groups. Blood lactate levels at rest were elevated (>2.0 mM) in 14/40 mitochondrial patients (mean = 2.1 ± 1.1 mM, range = 0.9–5.4 mM).

Peak exercise response
In MM patients, the average peak work capacity (0.88 ± 0.6 W/kg) and VO2 (16 ± 8 ml/kg/min) were significantly lower (P < 0.01) than in control subjects (work, 2.2 ± 0.7 W/kg; VO2, 32 ± 7 ml/kg/min) with a broad range in both groups (MM peak work capacity, 0.17–3.2 W/kg; peak VO2, 6–47 ml/kg/min; controls peak work capacity, 1.2–3.5 W/kg; VO2, 19.5–46.3 ml/kg/min). Mean peak cardiac output did not differ between the two groups (MM = 212 ± 56, range 123–368 ml/kg/min; controls = 212 ± 37, range 128–295 ml/kg/min). However, the capacity to increase oxygen extraction during exercise was severely attenuated in the MM group, as indicated by a low peak systemic a–vO2 difference (7.7 ± 3.5, range 2.7–17.6 ml/dl) compared with healthy subjects (15.2 ± 2.1, range 10.5–18.7 ml/dl) (Fig. 1A–D).

Peak work capacity and peak VO2 were directly proportional in both patients (r2 = 0.94) and healthy subjects (r2 = 0.83), consistent with the normal linear relationship between oxygen utilization and cycle ergometer work. The slopes of the regression depicting this relationship differed slightly (MM slope = 12.9, control slope = 9.6, P = 0.053), indicating that the oxygen cost at a given workload was slightly higher in the MM group compared with the control group (Fig. 2).

A direct relationship between peak capacity for O2 delivery (cardiac output) and O2 utilization is characteristic of healthy individuals and was present in our control subjects (r2 = 0.61, P < 0.01). In contrast, there was no correlation between peak cardiac output and VO2 in the patients (r2 = 0.08) (Fig. 3A). Instead, peak VO2 in MM patients correlated directly with peak systemic a–vO2 difference (r2 = 0.69, P < 0.01), thus linking the range of oxygen utilization in patients to the capacity for oxygen extraction within skeletal muscle (Fig. 3B). This relationship differs from the normal physiological response to exercise in healthy individuals, as indicated by the lack of correlation between peak VO2 and systemic a–vO2 difference in healthy subjects (r2 = 0.18).

During exercise, the increase in cardiac output relative to increase in oxygen uptake was exaggerated in most patients. The mean slope of ΔQ/ΔVO2 in the MM group was 3-fold greater than normal (MM = 15.0 ± 13.6, controls = 5.1 ± 0.7).

Also, the range was markedly variable in patients (MM = 3.3–73 in contrast to healthy subjects (4.3–6.7) (Fig. 4A). Ventilation during peak exercise was also in excess relative to VO2 in patients, as indicated by an elevated ventilatory equivalent for oxygen (peak VE/VO2 in MM = 65.1 ± 24.6, range 35–135; controls = 41.2 ± 7.4, range 23–55; P < 0.01) (Fig. 4B). Likewise, maximal RER was abnormally high in the MM group compared with controls (MM = 1.31 ± 0.31, range 0.94–2.4; controls = 1.14 ± 0.06, range 1.06–1.24; P < 0.01).

In healthy individuals, ΔQ/ΔVO2 is ~5 irrespective of the peak capacity for oxygen utilization. In contrast, in the MM patients, an increasingly severe mismatch between oxygen delivery and utilization accompanied more severely impaired muscle oxidative phosphorylation, as indicated by a negative exponential relationship between ΔQ/ΔVO2 and both peak oxygen utilization (r2 = 0.69, P < 0.01) and peak systemic a–vO2 difference (r2 = 0.92, P < 0.01; Fig. 5A). Similarly, a negative exponential correlation was evident for peak VE/VO2 relative to peak VO2 (r2 = 0.58, P < 0.01) and peak systemic a–vO2 difference (r2 = 0.53, P < 0.01; Fig. 5B). These results suggest that more exaggerated cardiovascular and ventilatory responses were related to lower peak capacity for oxidative phosphorylation as reflected in peak capacity for extraction of available oxygen from blood.

Blood lactate levels at peak exercise were high relative to peak workload and VO2 in MM patients compared with control subjects (MM exercise lactate/W = 0.26 ± 0.29 mM/W, controls = 0.05 ± 0.02 mM/W, P < 0.01; MM exercise lactate/VO2 = 0.60 ± 0.38 mM/ml/kg/min, controls = 0.28 ± 0.06 mM/ml/kg/min, P < 0.01). In the MM patients, the ratio of lactate (mM) to VO2 (ml/kg/min) at peak exercise correlated closely with both peak O2 utilization (r2 = 0.78, P < 0.01) and peak systemic a–vO2 difference (r2 = 0.60, P < 0.01; Fig. 6). In contrast, there was only a weak correlation between blood lactate levels at rest and both peak
oxygen utilization ($r^2 = 0.20, P < 0.05$) and peak systemic a–vO$_2$ difference ($r^2 = 0.22, P < 0.05$) in the MM patients.

The mutation load in 23 patients with heteroplasmic mtDNA defects ranged from 29 to 98%. Analysis of genotype–phenotype relationships in these patients revealed that increasing mutation load was associated with decreasing capacity for oxidative phosphorylation, as suggested by a negative exponential relationship between percentage mutation and peak O$_2$ uptake ($r^2 = 0.65, P < 0.01$), and between percentage mutation and peak systemic a–vO$_2$ difference ($r^2 = 0.70, P < 0.01$; Fig. 7). One patient (no. 17) harbouring a low mutation load despite severe physiological oxidative impairment was determined to be a statistical outlier (Hedges and Olkin, 1985) and was excluded from the regression analysis.

**Discussion**

Exercise intolerance is a fundamental consequence of impaired respiratory chain function due to pathogenic mutations of mitochondrial or nuclear DNA in skeletal muscle. It may be the sole manifestation of a respiratory chain defect (Andreu et al., 1999a; DiMauro, 1999; Pulkes et al., 2000) or it may occur in combination with muscle weakness and dysfunction of other organ systems. Exercise intolerance is difficult to assess clinically. Thus, determination of the prevalence and range of exercise limitations in MMs requires exercise testing. Furthermore, differentiating exercise limi-
Examination of exercise capacity indicates that it is attributable to physical deconditioning from that which is due to muscle respiratory chain dysfunction necessitates the independent assessment of cardiovascular fitness as well as an evaluation of the ability of working muscle to extract available oxygen. This study assesses each of these elements of exercise capacity in a large group of MMs.

The major findings of this study were that, in patients with MMs: (i) exercise capacity varied widely, attributable to varying levels of oxidative impairment; (ii) oxidative capacity was directly proportional to peak levels of extraction of available oxygen from blood (systemic a–vO₂ difference), representing a surrogate marker of muscle capacity for oxidative phosphorylation; (iii) exaggerated circulatory and ventilatory responses to exercise were governed by skeletal muscle oxidative capacity, in which more severely impaired oxidative phosphorylation elicited more exaggerated systemic responses to exercise; and (iv) in patients with defined mtDNA mutations, peak oxygen uptake and mitochondrial capacity for oxidative phosphorylation decreased in proportion to increasing mutation load in muscle.

**Exercise capacity and oxygen utilization**

The wide range of exercise and oxidative capacities in MM patients accounts for the clinical variability in severity of exercise intolerance in this patient population. Peak VO₂ was low in the majority of patients, and in some cases barely increased above the resting metabolic rate, commonly designated 1 metabolic equivalent (MET), defined as an oxygen utilization rate of 3.5 ml/kg/min (Wasserman, 1986). Patient functional capacity is often described in terms of METs. For example, activities of daily living including washing, driving and very slow walking (3.2 km/h) typically require a metabolic cost of ~4 METs (14 ml/kg/min), whereas

**Fig. 3** In MM patients, (A) peak oxygen uptake does not correlate directly with peak cardiovascular capacity for oxygen delivery (cardiac output) but does correlate closely with peak a–vO₂ difference (B).

**Fig. 4** The cardiovascular (A) and ventilatory (B) response to maximal exercise are depicted for 40 patients with MM (filled circles) and 32 healthy control individuals (filled squares). The mean values ± SD are shown to the right of the individual data for each group. * = significantly different from the control mean, P < 0.01.
walking at a moderate pace (5–6.5 km/h), slow stair climbing and skating require 5–7 METs (18–25 ml/kg/min), and slow jogging, bicycling and carrying heavy objects require >7 METs. Approximately two-thirds of our patient group could not exercise above 5 METs and would be classified in the ‘low’ fitness category (Wasserman, 1986). One-third of patients demonstrated exercise capacities within the range of our healthy sedentary controls (>20 ml/kg/min), including one patient who had a fitness level comparable with that of a healthy, conditioned individual.

This study illuminates the physiological mechanism that limits oxidative metabolism during physical activity in patients with MMs. Normally, from rest to peak exercise, the increased demand for oxygen by working muscle for aerobic energy production is met by both an increase in delivery of oxygenated blood to muscle by the circulation and an increase in the level of muscle O2 extraction from blood. In healthy individuals, there is a net increase in level of O2 extraction relative to O2 delivery during exercise. This is indicated by an exercise-related fall in O2 levels in venous blood (Taivassalo et al., 2002) and working muscle (Wariar et al., 2000), consistent with increased utilization of O2 by respiring mitochondria relative to the rate of increase in O2 delivery. Systemic a–vO2 difference therefore represents a marker of the capacity for mitochondrial oxidative phosphorylation. In healthy individuals, a–vO2 difference increases from 5 ml/dl at rest to ~15 ml/dl at peak exercise and does not limit oxygen utilization during exercise. This view is supported by the fact that peak a–vO2 difference does not correlate directly with peak oxidative capacity. Rather, oxygen delivery by the circulation is believed to be the principal determinant of aerobic performance, as indicated by findings that peak VO2 among healthy subjects correlates directly with peak cardiac output.

The majority of MM patients exhibited a blunted ability to increase systemic a–vO2 difference with exercise, consistent with previous findings of elevated O2 levels in venous blood from working muscle (Taivassalo et al., 2002) and high tissue O2 content (Bank and Chance, 1994). Furthermore, our data indicate that the degree of oxidative limitation during exercise in MMs relates directly to the capacity of muscle to extract available oxygen from blood. In other words, whereas peak work capacity in healthy individuals is limited by cardiovascular capacity to deliver O2 to working muscle, peak exercise capacity in patients with MMs is limited by muscle respiratory chain function. Our data indicate that an inability to increase systemic a–vO2 difference above 10 ml/dl is highly sensitive (80%) and specific (100%) for attributing low oxygen uptake to impaired mitochondrial function in patients with exercise intolerance. Cardiovascular capacity for oxygen delivery in most patients included in this investigation is comparable with that of healthy individuals.

**Circulatory and ventilatory responses to exercise**

These data demonstrate that skeletal muscle oxidative phosphorylation is a critical component in circulatory regulation during exercise. The exact mechanism responsible for the tight matching of oxygen delivery to oxygen utilization in healthy individuals is unclear but probably involves activation of neural reflexes via metaboreceptors in working muscle that are responsive to metabolites that reflect muscle oxidative demand (Haller and Vissing, 2000). Previous studies have indicated that an exaggerated increase in O2 delivery relative to muscle metabolic rate in exercise is a consistent feature of deficient muscle oxidative phosphorylation (Haller et al., 1989; Vissing et al., 1996; Haller and Vissing, 2000; Taivassalo et al., 2002). The prevalence of such a ‘hyperkinetic’ circulatory response to exercise in most of our MM patients underscores the requirement for a preserved capacity for muscle oxidative phosphorylation for normal coupling of oxygen delivery and utilization during exercise. Although our patients did not have evidence of cardiac involvement, combined myopathy and cardiomyopathy is common in mitochondrial disorders. In the setting of cardiac disease, a hyperkinetic circulatory response would be...
expected to have deleterious effects by increasing cardiac work.

This study is the first to relate the severity of the skeletal muscle oxidative defect to the severity of mismatch between the exercise increase in cardiac output and oxygen uptake ($\Delta Q/\Delta VO_2$). The data indicate that this normal close coupling becomes progressively distorted as the capacity for oxygen uptake and for muscle oxygen extraction becomes more impaired. Given the remarkably constant relationship between the exercise increase in oxygen uptake and corresponding increase in cardiac output in healthy individuals irrespective of age, gender or conditioning level and as reflected in our results from control subjects, we consider the cardiovascular exercise response to be consistent with an underlying defect in muscle oxidative phosphorylation when $\Delta Q/\Delta VO_2 \approx 7.0$ (100% specificity, 83% sensitivity).

The data also confirm previous reports that the ventilatory response to exercise is abnormal in many patients with MMs, as indicated by a level of pulmonary ventilation relative to peak oxygen uptake (VE/VO_2) that is excessive compared with control subjects (Haller et al., 1989; Flaherty et al., 2001). The ventilatory equivalent for oxygen (VE/VO_2) is an
indicator of breathing economy. During exercise, VE/VO₂ typically ranges between 30 and 40 l of air per litre of oxygen utilization in healthy individuals, with lower values in athletes and more conditioned individuals (Wasserman, 1986). This study demonstrates for the first time that exaggerated ventilation relative to oxygen utilization (higher VE/VO₂) in patients with MMs is related to the degree of oxidative impairment. Hyperventilation was more pronounced in patients with more severe oxidative defects, consistent with symptoms of exertional dyspnoea experienced by many patients. The mechanism underlying this hyperventilatory exercise response may relate to excess carbon dioxide production due to lactate buffering, as suggested by the finding of a correspondingly exaggerated respiratory exchange ratio (RER or VCO₂/VO₂). Alternatively, hyperventilation, like the hyperdynamic circulatory response, may be regulated by metabolic feedback from skeletal muscle that reflects limited oxidative phosphorylation relative to oxidative demand in working muscle.

**Oxygen utilization and lactic acidosis**

Lactic acidosis has often been used as an indicator of impaired oxidative metabolism and as a clinical marker for mitochondrial disorders. Although elevated lactate values at rest strengthen the possibility of a mitochondrial disorder, our data indicate diagnostic sensitivity to be only 35% at 100% specificity (>2.0 mM). Furthermore, our findings demonstrate that resting lactic acidosis is not a strong indicator of the degree of skeletal muscle oxidative impairment. In contrast, higher levels of lactate in relation to oxygen utilization during exercise in MM patients correlated closely with the severity of deficiency of mitochondrial oxidative phosphorylation as reflected in peak a–V O₂ difference.

**Oxygen utilization and mutation load**

While a direct correlation between impaired respiratory chain function and limited capacity to extract oxygen is implied by our results, insufficient biochemical data were available to evaluate the relationship between biochemical and physiological phenotypes. However, data regarding the mutation load were available in 23 of 30 patients with mtDNA mutations. A major finding of this study relates molecular genotype to physiological and clinical phenotype in patients with characterized heteroplasmic mutations of mtDNA. While there is evidence that the mutation load is inversely related to mitochondrial respiratory chain function in vitro (Chomyn et al., 1994), the correlation in vivo has been weak at best (Chinnery et al., 1997, 2000, 2001; Morgan-Hughes and Hanna, 1999). This is the first study to demonstrate that the mutation load in patients with various respiratory chain defects governs peak oxygen utilization and determines exercise capacity in patients with MMs. The data demonstrate an inverse relationship between the proportion of mutant mtDNA in skeletal muscle and muscle capacity for oxidative phosphorylation as reflected in peak systemic a–vO₂ difference.

**Conclusion**

This study underscores the utility of physiological exercise testing in the assessment of exercise tolerance and in the determination of functional severity of a skeletal muscle oxidative defect in patients with MMs. The non-invasive assessment of cardiac output during exercise is critical for revealing a hyperdynamic cardiovascular exercise response as well as for determining the capacity for skeletal muscle oxygen extraction. These measurements permit differentiation of reduced peak oxygen uptake that is due to poor physical conditioning from that due to an underlying genetic defect in mitochondrial oxidative metabolism. Particularly in the absence of other characteristic signs and symptoms, the exaggerated cardiovascular and ventilatory responses during exercise are sensitive indicators of an underlying oxidative impairment and account for the clinical prominence of tachycardia and dyspnoea that have been described in MM patients.

In conclusion, this study reveals a wide spectrum of oxidative limitations and exercise capacities in a heterogenous group of mitochondrial myopathies. It illuminates the relationship between severity of muscle oxidative defects and symptoms of exercise intolerance in MM patients. Furthermore, it provides insight into the regulatory mechanisms responsible for characteristic physiological responses to exercise in these patients, as well as evidence linking skeletal muscle mutation load to capacity for mitochondrial oxidative phosphorylation.

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