Effects of exercise on mitochondrial DNA content in skeletal muscle of patients with COPD

Luis Puente-Maestu,1,2 Alberto Lázaro,3 Alberto Tejedor,3 Sonia Camaño,3 Marta Fuentes,1,2 Miguel Cuervo,4 Beatriz Oláiz Navarro,5 Alvar Agustí6,7

ABSTRACT

Background Exhausting exercise reduces the mitochondrial DNA (mtDNA) content in the skeletal muscle of healthy subjects due to oxidative damage. Since patients with chronic obstructive pulmonary disease (COPD) suffer enhanced oxidative stress during exercise, it was hypothesised that the mtDNA content will be further reduced.

Objective To investigate the effects of exercise above and below the lactate threshold (LT) on the mtDNA content of skeletal muscle of patients with COPD.

Methods Eleven patients with COPD (67 ± 8 years; forced expiratory volume in 1 s (FEV1) 45 ± 8%ref) and 10 healthy controls (66 ± 4 years; FEV1 90 ± 7%ref) cycled 45 min above LT (85% peak oxygen uptake (V̇O2peak)) and 7 controls (65 ± 6 years; FEV1 50 ± 4%ref) and 7 patients with COPD but, because mitochondrial ROS production is augmented in such patients,6 11–13 we hypothesised that the fall in mtDNA content reported in healthy subjects10 will be enhanced in patients with COPD, particularly during fatiguing exercise above their lactate threshold (LT). Accordingly, this study sought to compare the dynamic changes induced by two types of exercise protocols (above and below the LT) in mtDNA content of the vastus lateralis muscle in patients with COPD and healthy controls. To get an insight into the potential molecular mechanisms, we also investigated the amount of ROS produced during exercise, the dynamic changes in the activity of manganese superoxide dismutase (MnSOD; EC 1.15.1.1), a major antioxidant enzyme, and of the expression of peroxisome proliferator-activated receptor-γ coactivator-1α (PGC-1α), a master regulator of mitochondrial biogenesis14 which appears to be abnormal in COPD.6 A better understanding of mitochondrial changes induced by exercise in the skeletal muscle of patients with COPD may be helpful for the design of improved rehabilitation strategies.

INTRODUCTION

Exercise limitation is a frequent complaint of patients with chronic obstructive pulmonary disease (COPD) and a major precipitator of their poor health status. Several cellular and molecular alterations that can contribute to exercise limitation have been described in the skeletal muscle of these patients.1–7 Our group has recently identified several mitochondrial abnormalities, including malfunction of the electron transport chain, abnormal kinetics of the mitochondrial permeability transition pore and excessive production of reactive oxygen species (ROS),8 9 that can also contribute to exercise limitation and skeletal muscle dysfunction in COPD.

In healthy subjects, fatiguing exercise causes a reduction in the mitochondrial DNA (mtDNA) content of skeletal muscle due to oxidative damage whereas low-intensity non-fatiguing exercise does not.10 This has not been investigated in patients with COPD but, because mitochondrial ROS production is augmented in such patients,6 11–13 we hypothesised that the fall in mtDNA content reported in healthy subjects10 will be enhanced in patients with COPD, particularly during fatiguing exercise above their lactate threshold (LT). Accordingly, this study sought to compare the dynamic changes induced by two types of exercise protocols (above and below the LT) in mtDNA content of the vastus lateralis muscle in patients with COPD and healthy controls. To get an insight into the potential molecular mechanisms, we also investigated the amount of ROS produced during exercise, the dynamic changes in the activity of manganese superoxide dismutase (MnSOD; EC 1.15.1.1), a major antioxidant enzyme, and of the expression of peroxisome proliferator-activated receptor-γ coactivator-1α messenger RNA (PGC-1α mRNA), a master regulator of mitochondrial biogenesis14 which appears to be abnormal in COPD.6 A better understanding of mitochondrial changes induced by exercise in the skeletal muscle of patients with COPD may be helpful for the design of improved rehabilitation strategies.

METHODS

Population

Patients with COPD (diagnosis according to the GOLD guidelines15) had moderate to severe airflow limitation (forced expiratory volume in 1 s (FEV1) <65% reference value), declared to have ceased smoking at least 6 months before enrolling, had not participated in a rehabilitation programme before and had no contraindication for exercise testing. Controls were non-smoking subjects with normal aerobic capacity and resting pulmonary function without any obvious lung, cardiac or other major disease after reviewing their medical information.

Study design

This is a prospective and controlled study. To determine peak oxygen uptake (V̇O2peak), all participants performed an incremental (20 W/min) symptom-limited exercise test on a cycle ergometer (ER-900, Jaeger, Hochberg, Germany) with continuous monitoring of oxygen saturation (Nellcor N-180, Pleasanton, California, USA) and...
breath-by-breath measurements of ventilation and pulmonary gas exchange (Quark-b2 system, Cosmed, Rome, Italy). Those who developed severe hypoxaemia (SaO₂ <87%) during the incremental test were excluded from further investigations. Then, 1–2 weeks later, the effects of two constant exercise protocols, above and below the LT, were investigated. The former entailed 3 min resting, 3 min unloaded pedalling and a total of 45 min pedalling (60 rpm) at 65% of V̇O₂peak whereas the latter entailed pedalling (60 rpm) at 50% of V̇O₂peak during 45 min. An arterial blood sample was anaerobically drawn immediately after exercise and analysed for blood gases and lactate concentration (Synthesis 1740, Instrumentation Laboratory, Lexington, Massachusetts, USA). Different subjects participated in the two exercise protocols (table 1) because of the high number of muscle biopsies needed (see limitations).

**Patient characterisation**

Spirometry was determined in the seated position with a Masterscope-PFT system (VYASIS, Hochberg, Germany); reported values correspond to those measured 15 min after the inhalation of 200 μg salbutamol. Fat-free mass was measured by bioelectrical impedance (Bodystat 1500, Bodystat Ltd, Douglas, Isle of Man, UK).

**Muscle biopsies**

Biopsies from the vastus lateralis muscle were obtained with an 18G Tru-Cut biopsy needle (Cardinal Health-España, Madrid, Spain) 2–7 days before the exercise test, immediately after it, and 1 h, 24 h and 1 week later. Two patients with COPD and three controls refused to be biopsied 1 week after exercise. The biopsy specimens were immediately frozen and stored at −80°C until analysis.

**Table 1 Characteristics of the study population**

<table>
<thead>
<tr>
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<th>Above LT</th>
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<th>Below LT</th>
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<tr>
<td></td>
<td>Controls (n=10)</td>
<td>COPD (n=11)</td>
<td>Controls (n=7)</td>
<td>COPD (n=7)</td>
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<td>Clinical data</td>
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<tr>
<td>Age (years)</td>
<td>66.5±4.3</td>
<td>67.2±8.4</td>
<td>56.7±8.9</td>
<td>65.0±6.5</td>
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<td>BMI (kg/m²)</td>
<td>26.2±2.4</td>
<td>24.8±3.2</td>
<td>27.3±7.0</td>
<td>25.7±2.5</td>
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<td>Lung function and peak exercise data</td>
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<td>FEV₁ (l)</td>
<td>2.9±0.4</td>
<td>1.4±0.3***</td>
<td>2.8±0.5</td>
<td>1.6±0.3***</td>
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<td>FEV₁ (% ref)</td>
<td>90.3±6.8</td>
<td>44.8±7.7***</td>
<td>92.5±5.6</td>
<td>49.9±3.8***</td>
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<td>Tlco (% ref)</td>
<td>89.1±12.4</td>
<td>56.7±16.1**</td>
<td>91.4±6.5</td>
<td>63.9±8.7**</td>
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<tr>
<td>PaO₂ at rest (mm Hg)</td>
<td>77±7</td>
<td>67±7**</td>
<td>83±3</td>
<td>66±5***</td>
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<tr>
<td>V̇O₂peak (l/min)</td>
<td>1.67±0.23</td>
<td>1.23±0.18**</td>
<td>1.73±0.34</td>
<td>1.34±0.29*</td>
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<tr>
<td>V̇O₂peak (% ref)</td>
<td>91±3.3</td>
<td>68±10.4***</td>
<td>90±2.3</td>
<td>71±11.9**</td>
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<td>V̇O₂ at LT (l/min)</td>
<td>1.03±0.13</td>
<td>0.73±0.15**</td>
<td>0.82±0.10</td>
<td>1.06±0.26**</td>
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<td>Work rate peak (W)</td>
<td>132±23</td>
<td>88±17***</td>
<td>143±35</td>
<td>99±27***</td>
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<tr>
<td>V̇O₂peak (l/min)</td>
<td>64.9±9.3</td>
<td>48.1±4.1***</td>
<td>74.9±16.2</td>
<td>53.8±16.5**</td>
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<td>Skeletal muscle results at rest</td>
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<tr>
<td>mtDNA/nDNA</td>
<td>1241±184</td>
<td>1104±183</td>
<td>1227±210</td>
<td>1082±229</td>
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<td>PGC-1α mRNA (arbitrary units)</td>
<td>1.02±0.12</td>
<td>0.86±0.44</td>
<td>0.99±0.24</td>
<td>0.76±0.16</td>
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<td>MnSOD (U/mg)</td>
<td>1.10±0.37</td>
<td>1.53±0.51*</td>
<td>0.9±0.2</td>
<td>1.33±0.39*</td>
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<td>Constant work load exercise data</td>
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<tr>
<td>Work rate (W)</td>
<td>86±14</td>
<td>57±25***</td>
<td>72±20</td>
<td>50±14**</td>
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<tr>
<td>V̇O₂peak (l/min)</td>
<td>1.55±0.14</td>
<td>1.13±0.26**</td>
<td>0.83±0.19</td>
<td>0.85±0.15*</td>
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<tr>
<td>V̇O₂peak (% ref)</td>
<td>61.3±5.7</td>
<td>44.6±5.9**</td>
<td>36.7±9.1</td>
<td>27.9±8.5*</td>
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<td>End exercise dyspnoea, CR10</td>
<td>5.0±2.2</td>
<td>4.1±1.4</td>
<td>3.6±1.8</td>
<td>2.0±1.0</td>
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<td>End exercise leg fatigue, CR10</td>
<td>7.5±1.8</td>
<td>6.8±1.6</td>
<td>4.7±2.1</td>
<td>2.4±1.5*</td>
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<tr>
<td>Total V̇O₂ (mmol)</td>
<td>2122±280</td>
<td>1515±227***</td>
<td>1113±223</td>
<td>865±187***</td>
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<td>Estimated ROS production (mmol/kg)</td>
<td>0.76±0.15</td>
<td>1.45±0.24***</td>
<td>0.4±0.1</td>
<td>0.81±0.16***</td>
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<tr>
<td>Pao₂ peak exercise (mm Hg)</td>
<td>80±4</td>
<td>66±6***</td>
<td>87±5</td>
<td>67±7***</td>
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<tr>
<td>Lactate end (mEq/l)</td>
<td>5.4±0.7</td>
<td>5.0±0.6</td>
<td>2.4±0.3</td>
<td>2.8±0.5</td>
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Values shown are mean±SD.

*p<0.05; **p<0.01; ***p<0.001 vs controls.

BMI, body mass index; CR10, Borg CR10 scale; FEV₁, forced expiratory volume in 1 s; FFMI, fat-free mass index; LT, lactate threshold; MnSOD, manganese superoxide dismutase; mtDNA, mitochondrial DNA; nDNA, nuclear DNA; Pao₂, arterial oxygen tension; % ref, percentage of predicted values; PGC-1α, peroxisome proliferator-activated receptor-γcoactivator-1α; ROS, reactive oxygen species; Tlco, carbon monoxide transfer factor; V̇O₂, minute ventilation.
Oxidative stress

The mtDNA oxidation assay used is based on two premises: (1) oxidative DNA damage blocks the progression of polymerase and causes decreased DNA amplification; and (2) the probability of oxidative lesions is lower in shorter DNA segments. Thus, the ratio between the amplification of a short (8.9 kb) and a long (207 kb) fragment (relative amplification; RA) is a marker that mirrors mtDNA oxidation (ie, the lower RA value the higher mtDNA oxidation). The two mtDNA fragments amplified were for the 8.9 kb fragment: mt5999F (5-TCTAAGCCTCC TTATTCGAGCCGA-3) and mt4388R (GAGATGTTGG ATGG-3) and the 207 bp fragment: mt4181F (5-TTATTCGAGCCGA-3) and mt14841R (5-TTTCATCATGCG-3).

The amount of ROS produced during exercise was estimated assuming that, in healthy subjects, 2% of mitochondrial V_o2 is diverted into the generation of ROS17 and that this is 2.5 times greater in patients with COPD.6

Finally, the activity of MnSOD in skeletal muscle biopsies was measured by the inhibition of nitroblue tetrazolium conversion by MnSOD into a blue tetrazolium salt method (Sigma-Aldrich, St Louis USA), as described by Beauchamp and Fridovich.18

Exercise below LT

The lactate concentration at the end of exercise did not reach 5 mEq/l, confirming that the intensity of exercise was below the LT (table 1). As shown in figure 1 (lower panel), low intensity exercise also induced significant changes in mtDNA/nDNA with respect to baseline in patients with COPD (−109±94
immediately after exercise, p=0.048; −220±9 1 h later, p=0.06; and −159±213 after 24 h, p=0.014), but not in controls (−33±4, p=0.12 immediately after exercise; −75±205, p=0.38 1 h later; and −53±94 after 24 h, p=0.39). It should be noted also that absolute mtDNA/nDNA changes were smaller when patients with COPD exercise below the LT than above it (p=0.007, p=0.024, p=0.131, respectively, for intergroup comparisons at the end of the exercise and 1 h, 24 h and 1 week later; figure 1). On the other hand, the MnSOD concentration was basically constant after exercise below the LT, so differences with controls were maintained through time (figure 2, lower panel) whereas changes in PGC-1α mRNA were still evident in patients with COPD but absent in controls (figure 3, lower panel).

**Potential associations**

Because previous studies in healthy subjects ascribed a key pathogenic role to oxidative stress in the observed decrease in the mtDNA content in skeletal muscle, we explored potential relationships between the estimated production of ROS during exercise and changes from rest to 1 h after exercise in mtDNA/nDNA in the entire population of subjects (patients and controls) studied both above and below the LT (figures 4 and 5). Our data confirm that a higher production of ROS during exercise was associated with a significant increase in mRNA/nDNA (figure 4A) and a larger change in MnSOD (figure 4C). Furthermore, we found a good correlation between the estimated ROS production and mtDNA relative amplification (figure 4B), suggesting that the former is a reasonably good proxy of the amount of oxidative stress during exercise.

On the other hand, we extended previous observations by showing that the estimated ROS production during exercise was also associated with a significant increase in PGC-1α mRNA 1 h after exercise (figure 4D). Likewise, we observed significant correlations between the total amount of oxygen consumed per kg of fat-free mass during exercise and these same muscle variables (figure 5). Finally, we found that changes in PGC-1α mRNA were also significantly related to changes in mtDNA/nDNA (r=−0.52, p<0.001) and MnSOD (r=0.40, p=0.017) (data not shown).

**DISCUSSION**

Our results confirm that, in healthy subjects, fatiguing exercise induces a fall in skeletal muscle mtDNA content and upregulates PGC-1α mRNA expression. We extend these observations for the first time to patients with COPD where, as hypothesised, changes are enhanced (figures 1 and 3), probably in relation to augmented oxidative stress (figures 4 and 5). We also highlight the different recovery dynamics of PGC-1α mRNA expression and mtDNA changes; the former returns to normal values 24 h after exercise (figure 5) whereas the latter takes longer to recover (figure 1). Our results also show that these effects are less marked when patients exercise below the LT (figures 1–3).

**Previous studies**

A number of cellular and molecular abnormalities have been described in the skeletal muscle of patients with COPD including mitochondrial changes. The lower PGC-1α mRNA expression observed in skeletal muscle biopsies of patients with COPD at rest are in keeping with these previous observations and may be the consequence of inactivity or a switch towards type II fibres (known to express less PGC1α mRNA and reported in COPD). To our knowledge, however, this is the first study that has specifically investigated the effects of exercise, both below and above the LT, on these markers in these patients. Overall, the pattern of response to exercise of mRNA/nDNA and PGC-1α mRNA observed in patients with COPD is similar to that described in healthy subjects but, for a given exercise intensity, mtDNA/nDNA changes are magnified in COPD (figures 1 and 3).

**Potential mechanisms**

At rest the mtDNA/nDNA ratio was lower in patients with COPD. This is consistent with several abnormalities previously

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**Figure 2** Time course of mean±SEM changes in manganese superoxide dismutase (MnSOD) in controls (closed circles) and patients with chronic obstructive pulmonary disease (COPD) (open circles) exercising at high intensity (upper panel) and low intensity (lower panel). *p<0.05 isotime COPD vs controls. LT, lactate threshold.

**Figure 3** Time course of mean±SEM changes in peroxisome proliferator-activated receptor-γcoactivator-1α (PGC-1α) in controls (closed circles) and patients with chronic obstructive pulmonary disease (COPD) (open circles) exercising at high intensity (upper panel) and low intensity (lower panel). *p <0.05; ***p <0.001 isotime COPD vs controls. LT, lactate threshold.
described in these patients including decreased density of mitochondria in the vastus lateralis muscle, reduced citrate synthase activity and/or a higher proportion of type II fibres with less oxidative capacity and lower PGC-1α-mRNA expression (as was also observed in our patients).

We confirmed that the mtDNA content decreases in healthy subjects after fatiguing exercise and we show for the first time that this is enhanced in patients with COPD. As previously suggested, our results support a pathogenic role of oxidative stress because: (1) it is well established that patients with COPD produce a larger amount of ROS than healthy controls during exercise; (2) we found both temporal and statistical correlations between the estimated ROS burden produced during exercise and changes in mtDNA content (figure 4); (3) we observed a biological gradient between the expected ROS production and the changes in mtDNA/nDNA that were reduced in patients with COPD exercising below their LT (figure 1) who also have less oxidative stress (table 1 and figures 4 and 5); (4) the fall in mtDNA after exercise was related to changes in MnSOD concentration and PGC-1α mRNA content (figure 4), both known to be related to oxidative stress; and (5) it is biologically plausible that, as the main subcellular site of ROS production is the mitochondria, the concentration of ROS in the mitochondrial matrix is 5–10-fold higher than in the cytosol or nucleus and the level of oxidised bases in mtDNA is 10–20-fold higher than in nDNA. In addition, unlike nDNA, mtDNA lacks protective histones and is endowed with relatively low DNA repair activity. It is therefore entirely plausible that enhanced ROS production during exercise in the skeletal muscle of patients with COPD may contribute to amplifying the decrease in mtDNA in these patients (figures 1 and 4). Together these arguments support a mechanistic role for oxidative stress in the enhanced decrease in mtDNA content in the skeletal muscle of patients with COPD after exercise.

Clinical implications
Our observations may be relevant for rehabilitation programmes in COPD because oxidative mtDNA damage and PGC-1α mRNA expression are prerequisites for adaptation to training. In this context it is noteworthy that moderate intensity exercise (below the LT) induced both a significant decrease in mtDNA/ nDNA and an increase in PGC-1α mRNA expression in the patients with COPD.

Figure 4 Correlation between estimated production of reactive oxygen species (ROS) during exercise and changes from rest to 1 h after exercise in (A) mitochondrial DNA/nuclear DNA (mtDNA/nDNA) ratio, (B) mtDNA oxidative damage (relative amplification), (C) manganese superoxide dismutase (MnSOD) and (D) peroxisome proliferator-activated receptor-γ coactivator-1α (PGC-1α) mRNA in controls (closed symbols) and patients with chronic obstructive pulmonary disease (COPD) (open symbols) studied both above (circles) and below the lactate threshold (triangles). FFM, fat-free mass.

The response of PGC-1α mRNA to exercise indicates that, at least in the patients with COPD studied here who were not characterised by a low body mass index (table 1), the first step for mitochondrial biogenesis and type I fibre differentiation is not altered and that, consequently, other mechanisms should be implicated in the pathobiology of muscle atrophy in COPD. This observation also raises concerns about the potential utility of antioxidant supplementation during rehabilitation as they could dampen ROS signalling and interfere with mitochondrial biogenesis.

Potential limitations
Some potential limitations of our study deserve discussion. First, the sample size was relatively small and biopsy specimens were not available 1 week after exercise in a few subjects. However, we believe that our results are valid because they were internally consistent within each group. Second, different subjects participated in the two exercise protocols (below and above the LT) because the considerable number of biopsies involved in the study precluded other alternatives. However, the baseline characteristics of the patients and controls in both protocols were similar (table 1) and the biological response of healthy subjects to exercise, both above and below the LT, was similar to that previously described. Third, ROS production during exercise was not measured directly but was estimated from published data. However, we think that the correlation observed with several independent variables such as mtDNA/nDNA, MnSOD and oxidised mtDNA support our interpretation of the results. Finally, patients with COPD were treated with β2 agonists but these drugs do not appear to influence mitochondrial biogenesis signals, including PGC-1α.

Conclusions
Our study shows that exercising at the typical intensity and duration of training sessions in pulmonary rehabilitation programmes produces a significant decrease in the mtDNA content of skeletal muscle in patients with COPD and over-expression of PGC-1α mRNA, probably in relation to enhanced oxidative stress. Interestingly, the changes are minimised but not abolished with non-fatiguing exercise below the LT, and this may be relevant for the training effect seen in these patients training below the LT.

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Competing interests None.

Patient consent All participants gave written informed consent after being made fully aware of the goals and potential risks of the study.

Ethics approval This study was conducted with the approval of the Committee for Ethics in Human Research of Madrid Sanitary Area 1 and all aspects of the study comply with the Declaration of Helsinki.

Provenance and peer review Not commissioned; externally peer reviewed.

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