Lung transplantation

Breathing pattern and chest wall volumes during exercise in patients with cystic fibrosis, pulmonary fibrosis and COPD before and after lung transplantation

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ABSTRACT

Background Pulmonary fibrosis (PF), cystic fibrosis (CF) and chronic obstructive pulmonary disease (COPD) often cause chronic respiratory failure (CRF).

Methods In order to investigate if there are different patterns of adaptation of the ventilatory pump in CF, in three groups of lung transplant candidates with PF (n=9), forced expiratory volume in 1 s (FEV1)=37±3% predicted, forced vital capacity (FVC)=32±2% predicted), CF (n=9, FEV1=22±3% predicted, FVC=30±3% predicted) and COPD (n=21, FEV1=21±1% predicted, FVC=46±2% predicted), 10 healthy controls and 16 transplanted patients, total and compartmental chest wall volumes were measured by opto-electronic plethysmography during rest and exercise.

Results Three different breathing patterns were found during CRF in PF, CF and COPD. Patients with COPD were characterised by a reduced duty cycle at rest and maximal exercise (34±1%, p<0.001), while patients with PF and CF showed an increased breathing frequency (49±6 and 34±2/min, respectively) and decreased tidal volume (0.75±0.10 and 0.79±0.07 litres) (p<0.05). During exercise, end-expiratory chest wall and rib cage volumes increased significantly in patients with COPD and CF but not in those with PF. End-inspiratory volumes did not increase in CF and PF. The breathing pattern of transplanted patients was similar to that of healthy controls.

Conclusions There are three distinct patterns of CRF in patients with PF, CF and COPD adopted by the ventilatory pump to cope with the underlying lung disease that may explain why patients with PF and CF are prone to respiratory failure earlier than patients with COPD. After lung transplantation the chronic adaptations of the ventilatory pattern to advanced lung diseases are reversible and indicate that the main contributing factor is the lung itself rather than systemic effects of the disease.

INTRODUCTION

The indications for lung transplantation have spanned the spectrum of lung diseases, with chronic obstructive pulmonary disease (COPD), idiopathic pulmonary fibrosis (PF) and cystic fibrosis (CF) being the three most frequent diseases in which this procedure is performed. The distribution primarily reflects the natural history of these lung diseases, with progressive chronic respiratory failure ultimately leading to death unless a transplantation is possible. Current criteria for lung transplantation include a clinically and physiologically severe disease with ineffective or unavailable medical treatment and limited life expectancy of <2–3 years.1 2 Since there are marked disease-specific differences, with a much lower survival rate for patients with PF than for patients with CF or COPD, there are disease-specific guidelines for referral.3 4 In individual patients it is difficult to predict the clinical course. Given a similar impaired pulmonary function, some patients stay stable for long periods, while others develop respiratory failure within a short period.

Altered patterns of breathing during rest and exercise are observed in these lung diseases.5 In their classical studies, Otis, Fenn and Rahn indicated how minimal work of breathing is determined by the different types of load imposed on the ventilatory pump, namely elastic and resistive.5 6 When, like in PF, the elastic load increases, minimal work of breathing would require a rapid shallow breathing pattern. When, like in COPD, the lungs are hypercompliant and the airways obstructed, minimal work would entail a slow deep breathing pattern. When, like in CF, both resistive and elastic load are increased, it could be difficult to predict what the breathing pattern should be to minimise the work of breathing.

The major question of the present study was whether in chronic respiratory failure due to PF, CF and COPD there are different ways of coping with the disease resulting in different patterns of adaptation of the ventilatory pump in very advanced disease state. Therefore, we tested the hypothesis that the different characteristics of these diseases lead to different breathing patterns at rest and during exercise and that chronic adaptations of the ventilatory pattern are reversible after lung transplantation.

METHODS

Subjects

Thirty-nine patients on the waiting list for lung transplantation in the university clinic of Homburg with severe CF (n=9), PF (n=9) and COPD (n=21) diagnosed by accepted criteria were recruited into the study. All patients with COPD, four patients with PF and none of the patients with CF had been former smokers and had abstained from smoking for at least 6 months.

In addition, we studied 16 transplanted patients (T), 5 with COPD (T-COPD), 4 with CF (T-CF) and 7 with PF (T-PF) in a stable condition at least 3 months after lung transplantation. Of these, 7
patients (4 T-CF and 3 T-COPD) had received double lung and 9
(2 T-COPD, 7 T-PF) single lung transplantation. Analysis of
their pulmonary function data before transplantation split into
the three diseases did not show any significant difference from
the corresponding groups (see online data repository).

All patients were studied during an ongoing continuous pulmonary rehabilitation programme before lung trans-
planted and were familiar with physiological exercise testing.
Components of the pulmonary rehabilitation programme
included comprehensive evaluation of medical and nutritional
needs, setting of goals for education and exercise training, ex-
cise training (endurance, lower extremity, flexibility, strengthen-
ing and upper extremity), education about medical treatments
and nutritional counselling.

Ten non-smoking volunteers recruited from hospital staff
were considered as the healthy control (HC) group. They
followed the same measurement protocol except for 6 min walk
and blood gas analysis. Characteristics of both patients and
controls are reported in table 1.

The protocol was approved by the local research ethics
committee and informed consent was obtained from all patients.

Study design
Initially, patients were assessed for pulmonary function.
Spirometry, lung transfer factor for carbon monoxide and
subdivisions of lung volumes by body plethysmography
(Masterlab; Jaeger, Wuerzburg, Germany) were performed
according to the European Respiratory Society (ERS)
recommendations.9

Thereafter, all patients underwent a standardised 6 min walk
test9 followed by a resting period of 60 min. Finally an
incremental exercise test was performed on an electromagneti-
cally braked cycle ergometer (Ergoselect 200P; Ergoline, Bitz,
Germany) with continuous measurements throughout rest
(3 min), unloaded pedalling (3 min) and incremental exercise
(stepwise workload increments of 5 or 10 W every 2 min) up to
the limits of exercise tolerance. Patients were verbally encour-
aged before and during the test, to make a maximal effort.
Standard criteria for termination of exercise were applied.10 All
patients terminated exercise due to intolerable dyspnoea or
exhaustion.

All waiting list patients used supplemental oxygen at rest and
during the exercise tests. Cardiac frequency and arterial oxygen
saturation measured by pulse oximetry were monitored continu-
ously (SC 6000P, Siemens Medical Systems, Danvers,
Massachusetts, USA). Blood pressure was measured by arm cuff
every 2 min. Borg ratings of dyspnoea and leg discomfort were
assessed every 2 min at the end of each workload throughout
exercise using a modified 1–10 Borg scale.11

Opto-electronic plethysmography (OEP)
During the exercise test, chest wall volumes were measured on
a breath-by-breath basis by OEP (OEPsystem, BTS, Milano,
Italy). OEP is based on six calibrated video cameras (placed three
in front of the subject and three behind) which record the
position of 89 reflective markers placed on the front and back
over the chest wall from the clavicles to pubis.12 13 To prevent
the arms from obscuring the markers, during cycling the
patients grasped handles positioned laterally at the mid sternum
level. From the three-dimensional coordinates of the markers
obtained by stereo-photogrammetry, a specialised software
based on the Gauss theorem provided continuous measurement
of the volume of the total chest wall (V CW), split into rib cage
(V RC) and abdomen (V AB), with V CW = V RC + V AB.

From chest wall volume measurements the complete set of
ventilatory parameters including tidal volume (ΔV CW),
breathing frequency (f B), minute ventilation (f B×ΔV CW), total
respiratory cycle time (T R), inspiratory time (T I), mean
inspiratory (ΔV CW/T I) flow rate and duty cycle (T I/T R) was
determined. End-expiratory (EE) and end-inspiratory (EI)

<p>| Table 1 Patient characteristics: anthropometric characteristics, blood gases, spirometric values, subdivision of lung volumes and exercise tolerance in patients with pulmonary fibrosis, cystic fibrosis, chronic obstructive pulmonary disease (COPD), healthy control subjects and transplanted patients |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|</p>
<table>
<thead>
<tr>
<th>Pulmonary fibrosis</th>
<th>Cystic fibrosis</th>
<th>COPD</th>
<th>Healthy controls</th>
<th>Transplanted</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>9</td>
<td>9</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>Age (years)</td>
<td>53.89 ± 4.19</td>
<td>32.89 ± 3.05</td>
<td>54.43 ± 1.02</td>
<td>52.20 ± 2.62</td>
</tr>
<tr>
<td>Gender (M/F)</td>
<td>4/5</td>
<td>5/4</td>
<td>8/13</td>
<td>5/5</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>170.22 ± 3.87</td>
<td>167.78 ± 3.84</td>
<td>167.93 ± 1.99</td>
<td>172.85 ± 3.50</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>64.21 ± 4.95</td>
<td>52.33 ± 3.17</td>
<td>58.51 ± 2.29</td>
<td>71.32 ± 2.88</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>21.98 ± 1.13</td>
<td>18.33 ± 0.57</td>
<td>20.77 ± 0.76</td>
<td>23.92 ± 0.82</td>
</tr>
<tr>
<td>PO₂ (kPa)</td>
<td>8.19 ± 0.81</td>
<td>9.00 ± 0.48</td>
<td>9.05 ± 0.35</td>
<td>—</td>
</tr>
<tr>
<td>PCO₂ (kPa)</td>
<td>4.94 ± 0.37</td>
<td>5.39 ± 0.32</td>
<td>5.59 ± 0.23</td>
<td>—</td>
</tr>
<tr>
<td>FVC (litres)</td>
<td>1.20 ± 0.18</td>
<td>1.21 ± 0.13</td>
<td>1.55 ± 0.10</td>
<td>4.04 ± 0.40</td>
</tr>
<tr>
<td>FVC (% predicted)</td>
<td>31.71 ± 2.55</td>
<td>29.73 ± 3.34</td>
<td>45.66 ± 2.50</td>
<td>101.80 ± 1.74</td>
</tr>
<tr>
<td>FEV₁ (litres)</td>
<td>1.17 ± 0.19</td>
<td>1.07 ± 0.08</td>
<td>0.59 ± 0.03</td>
<td>3.35 ± 0.30</td>
</tr>
<tr>
<td>FEV₁ (% predicted)</td>
<td>37.88 ± 3.56</td>
<td>22.46 ± 2.81</td>
<td>20.77 ± 1.15</td>
<td>102.69 ± 3.35</td>
</tr>
<tr>
<td>FEV₁/FVC (%)</td>
<td>92.40 ± 2.06</td>
<td>65.40 ± 4.10</td>
<td>31.66 ± 2.09</td>
<td>80.84 ± 1.74</td>
</tr>
<tr>
<td>TGV (litres)</td>
<td>1.93 ± 0.25</td>
<td>4.48 ± 0.48</td>
<td>7.22 ± 0.46</td>
<td>3.55 ± 0.35</td>
</tr>
<tr>
<td>TGV (% predicted)</td>
<td>61.67 ± 7.46</td>
<td>149.53 ± 13.92</td>
<td>241.07 ± 12.73</td>
<td>110.81 ± 7.60</td>
</tr>
<tr>
<td>RV (litres)</td>
<td>1.50 ± 0.26</td>
<td>4.16 ± 0.49</td>
<td>5.69 ± 0.49</td>
<td>2.44 ± 0.16</td>
</tr>
<tr>
<td>RV (% predicted)</td>
<td>74.57 ± 13.17</td>
<td>253.74 ± 24.89</td>
<td>287.63 ± 21.29</td>
<td>121.36 ± 6.76</td>
</tr>
<tr>
<td>TLC (litres)</td>
<td>2.77 ± 0.34</td>
<td>5.65 ± 0.54</td>
<td>8.46 ± 0.48</td>
<td>6.63 ± 0.57</td>
</tr>
<tr>
<td>TLC (% predicted)</td>
<td>45.84 ± 3.96</td>
<td>96.19 ± 7.63</td>
<td>149.54 ± 6.28</td>
<td>105.96 ± 4.27</td>
</tr>
<tr>
<td>RV/TLC (% predicted)</td>
<td>52.73 ± 5.65</td>
<td>72.41 ± 3.05</td>
<td>71.83 ± 3.95</td>
<td>37.46 ± 1.39</td>
</tr>
<tr>
<td>Maximum workload (W)</td>
<td>13.36 ± 5.95</td>
<td>25.56 ± 6.03</td>
<td>16.67 ± 2.22</td>
<td>159.00 ± 17.35</td>
</tr>
<tr>
<td>Maximum workload (% predicted)</td>
<td>7.6 ± 3.3</td>
<td>17.2 ± 3.5</td>
<td>13.8 ± 2.2</td>
<td>97.6 ± 5.0</td>
</tr>
<tr>
<td>6MW distance (m)</td>
<td>199.60 ± 65.97</td>
<td>287.00 ± 54.21</td>
<td>229.50 ± 26.07</td>
<td>(n=5)</td>
</tr>
</tbody>
</table>

F, female; FEV₁, forced expiratory volume in 1 s; FVC, forced vital capacity; M, male; 6MW, 6 minute walk; RV, residual volume; TGV, thoracic gas volume; TLC, total lung capacity.
Table 2  Ventilatory pattern at maximal exercise

<table>
<thead>
<tr>
<th>Pulmonary fibrosis (PF)</th>
<th>Cystic fibrosis (CF)</th>
<th>COPD</th>
<th>Healthy controls (HC)</th>
<th>Transplanted (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>9</td>
<td>9</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>Vt (litres)</td>
<td>0.75±0.10</td>
<td>0.79±0.07</td>
<td>1.25±0.08</td>
<td>2.60±0.33</td>
</tr>
<tr>
<td>ΔVrc (%)</td>
<td>41.3±7.8</td>
<td>40.0±4.7</td>
<td>50.0±3.2</td>
<td>47.6±3.9</td>
</tr>
<tr>
<td>ΔVab (%)</td>
<td>58.7±7.8</td>
<td>60.0±4.7</td>
<td>50.0±3.2</td>
<td>52.4±3.9</td>
</tr>
<tr>
<td>Ttot (s)</td>
<td>1.45±0.24</td>
<td>1.86±0.13</td>
<td>3.16±0.23</td>
<td>2.24±0.24</td>
</tr>
<tr>
<td>Tins (s)</td>
<td>0.62±0.10</td>
<td>0.81±0.07</td>
<td>1.03±0.06</td>
<td>1.09±0.11</td>
</tr>
<tr>
<td>Texp (s)</td>
<td>0.83±0.15</td>
<td>1.05±0.06</td>
<td>2.12±0.18</td>
<td>1.15±0.13</td>
</tr>
<tr>
<td>Duty cycle (Texp/Ttot, %)</td>
<td>43.8±1.9</td>
<td>43.5±0.9</td>
<td>33.9±1.1</td>
<td>** vs HC, T, PF, CF, HC, T</td>
</tr>
<tr>
<td>Breath frequency (min⁻¹)</td>
<td>49.4±6.1</td>
<td>33.9±2.3</td>
<td>213.1±1.6</td>
<td>30.0±3.2</td>
</tr>
<tr>
<td>Minute ventilation (l/min)</td>
<td>34.8±5.4</td>
<td>26.8±2.7</td>
<td>24.9±1.4</td>
<td>73.1±8.9</td>
</tr>
<tr>
<td>Mean inspiratory flow (Vt/Tins, l)</td>
<td>1.34±0.17</td>
<td>1.04±0.12</td>
<td>1.25±0.06</td>
<td>** vs HC, T</td>
</tr>
<tr>
<td>Borg breath</td>
<td>4.2±1.2</td>
<td>5.7±1.3</td>
<td>5.8±0.6</td>
<td>4.0±0.6</td>
</tr>
<tr>
<td>Borg leg</td>
<td>2.5±1.2</td>
<td>5.1±1.3</td>
<td>5.7±0.6</td>
<td>5.7±0.6</td>
</tr>
</tbody>
</table>

*p<0.05, **p<0.01, ***p<0.001

Te, expiratory time; Ti, inspiratory time; Ttot, total respiratory cycle time; Vt, tidal volume; ΔVab, percentage contribution of abdomen to tidal volume; ΔVrc, percentage contribution of rib cage to tidal volume.
followed a completely different pattern, in which the increase in minute ventilation was achieved almost exclusively by increasing breathing frequency (rapid and shallow breathing). Figure 1B shows that transplanted patients had a frequency—tidal volume pattern almost identical to that of healthy subjects. Minute ventilation can additionally be considered as the product of mean inspiratory flow ($V_{TI}$, x-axis) and duty cycle ($TI/T_{TOT}$). In figure 2A these two variables are plotted against each other in patients with PF, CF and COPD and in healthy controls. Patients with PF and CF showed a pattern similar to that of controls. In contrast, patients with COPD had a distinct pattern, with a significantly lower duty cycle and increased mean inspiratory flow at any minute ventilation. Figure 2B shows that after transplantation, all patients restored a duty cycle—mean inspiratory flow pattern similar to that of healthy controls, particularly at the lower level of exercise.

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exercise compared with rest). In patients with COPD, both EE (p = 0.069 and p = 0.042, unloaded and maximal exercise compared with rest, respectively) and EI (p = 0.028 unloaded exercise vs rest; p = 0.005 unloaded vs maximal exercise; p = 0.001 maximal exercise vs rest) increased or tended to increase during exercise. The increase of EI, however, was higher and consequently tidal volume increased significantly during exercise (p = 0.067 unloaded exercise vs rest; p = 0.004 maximal exercise vs rest). Only 3 out of 21 patients with COPD decreased EE volume at maximal exercise. The comparison between the overall volume data in the three patient groups before lung transplantation revealed that EI and tidal volumes were higher in COPD than in PF and CF (p < 0.001). In the transplanted patients, EE, EI and tidal volumes were similar to those of healthy controls at any given level of workload.

Figure 4 illustrates how EE and EI volume variations are divided into the rib cage (top panels) and abdominal (bottom panels) compartments. In healthy subjects, the increase of EI volume of the total chest wall compared with rest was due to both the rib cage and the abdomen (p < 0.001), while the decrease of EE volume was totally achieved in the abdomen (p < 0.001). In patients with PF, no volume changes occurred in either compartment. In patients with CF, the increase of total EE and EI chest wall volumes at maximal exercise compared with rest was totally due to the rib cage compartment (p = 0.003 and p = 0.005, respectively). The increase in tidal volume was mainly due to the abdomen. In patients with COPD, the increase in total EI chest wall volume compared with rest was due to both the rib cage (p < 0.001) and the abdomen (p = 0.017). On the other hand, the increase of total EE chest wall volume compared with rest was only due to the rib cage (p < 0.001). The increase in tidal volume compared with rest was due to both the rib cage (p = 0.058) and abdomen (p = 0.016). In the transplanted patients, EE, EI and tidal volumes of the rib cage and the abdomen were similar to those of healthy controls.

**DISCUSSION**

This study represents the first systematic comparison of breathing pattern and chest wall volume changes during quiet breathing and exercise between patients with PF, CF or COPD, transplanted patients and healthy subjects. The ventilatory pattern of these diseases has been described so far only separately, 8-15 and a comprehensive comparison between the most advanced disease stages and healthy controls or transplanted patients has not been available.

The main finding of this study is that each disease results in a different breathing pattern during chronic respiratory failure. The reduced duty cycle represents the main feature of alteration in COPD, while the increased breathing frequency and decreased tidal volume is the characteristic distinguishing patients with PF or CF.

**Patients with COPD**

In patients with COPD expiratory flow limitation determines longer expiratory time, inducing significantly lower values of the duty cycle and a limited minute ventilation both at rest and during exercise (~30% compared with age-matched healthy subjects). In a recent paper, 24 the duty cycle in patients with COPD with less advanced disease was also decreased compared with normal, being, however, considerably higher than in our waiting list patients. These findings suggest that the duty cycle is inversely correlated with the severity of the disease. Previous data have also shown that this parameter can be used in patients with COPD to predict the need for mechanical ventilation in acute exacerbations. 21 Another significant abnormality in the pattern of breathing of patients with COPD is the high inspiratory flow rate resulting from the low duty cycle and high minute ventilation. A high inspiratory flow rate in the face of airways obstruction indicates a greater than normal inspiratory pressure drop with an abnormally high central inspiratory drive. This is probably a major cause of dyspnoea and thus exercise limitation in COPD.

Our data also show that patients with COPD exhibit a preserved tidal volume at rest. During exercise it increases both in the rib cage and in the abdomen, but it is limited by dynamic hyperinflation of the chest wall. This is located in the rib cage. 13, 22 In our waiting list patients, 5 out of 21 showed an euvalvolic pattern; that is, a decrease of EE chest wall volume during exercise. Interestingly, these three patients were the ones showing the best predicted forced expiratory volume in 1 s (FEV1) in the overall group of patients with COPD, suggesting that dynamic hyperinflation occurs mainly in the most severe patients. 13
Frequency/tidal volume variations during both quiet breathing and exercise resembled those found in healthy subjects and are in agreement with data obtained by respiratory inductive plethysmography in patients with moderate COPD. It has been shown that in patients with COPD, hypercapnia and rapid shallow breathing are very closely related during acute respiratory failure. In our results obtained in patients with COPD this pattern did not occur, even at very severe stages of the disease. The reason for this might be that our patients awaiting transplantation were highly selected, receiving carefully monitored optimal treatment, and therefore might not be representative of the entire population of patients with severe disease.

Patients with PF
Patients with PF exhibit rest a rapid and shallow breathing with low values of tidal volume and very high breathing frequencies. Possible mechanisms involved in this pattern of breathing include increased lung elastance, perceived as increasing load by mechanoreceptors, and stimulation of intrapulmonary receptors, such as rapidly adapting and J receptors. Rib cage tidal volume is decreased both at rest and during exercise, probably due to the increased rigidity of the lung and consequently to the reduced expansion of the rib cage compartment apposed to the lung. Total minute ventilation is higher than normal, permitting an increased alveolar ventilation to overcome disease-specific gas exchange alteration. Additionally, a high dead space occurring with a low tidal volume might contribute to this altered breathing pattern. Excessive dead space ventilation is common in interstitial lung diseases, leading to a higher minute ventilation and ventilatory work during exercise. At maximal exercise the doubled minute ventilation is significantly higher than in normal subjects but lower than in patients with PF, resulting in high minute ventilation that, associated with hypercapnia, indicates a grossly abnormal alveolar dead space. During exercise, these patients are able to increase tidal volume slightly (p < 0.01) mainly by increasing abdominal displacement. These data are in agreement with those of Keochkerian et al., who reported that during exercise, children with CF, even those not suffering from advanced disease, showed signs of rapid and shallow breathing and an increase in the ventilatory response. This was essentially due to an increase in the mean inspiratory flow, which in turn suggests an inspiratory flow limitation. Indeed, our patients with CF have dynamic hyperinflation of the chest wall. Likewise, in patients with COPD, the increase in EE chest wall volume is located in the rib cage compartment. Our results show that patients with CF are restricted at end-inspiration but dynamically hyperinflate with exercise, while patients with PF are restricted at both end-expiration and end-inspiration.

The situation in patients with CF depends on the severity of the disease. With our data one can speculate that during the progression of the disease in CF, frequency/tidal volume ratios gradually tend from normal values to those observed in patients with PF. These functional changes might reflect the structural transition from the progressive airflow obstruction, caused by mucus plugging and inflammation within the bronchial walls, to the destruction of the lung parenchyma secondary to bronchectasis. Our data reveal that in several aspects patients with CF have an intermediate pattern between that of patients with COPD and that of patients with PF, which is somewhat closer to PF than COPD in the most advanced states of disease.

Transplanted patients
Our data show that lung transplantation restores a normal breathing pattern regardless of the underlying disease. The maximal exercise capacity, however, is significantly lower than...
that of healthy subjects. Several factors contributing to the reduced exercise performance have been discussed, including cardiovascular and muscular deconditioning due to inactivity and intake of immunosuppressive agents. Additionally, it has been reported that patients transplanted for diseases that produce chronic hyperinflation, such as CF and emphysema, may have preoperative structural changes in rib cage shape that persist in part after transplantation and lead to persistent increases in functional residual capacity and residual volume. These alterations, when still present after transplantation, might contribute to decreased exercise tolerance.

It was not our purpose to analyse in detail differences between the three patient groups after lung transplantation or differences between single and double lung transplantation. Nevertheless, no significant differences were found in the three diseases after transplantation either in the breathing pattern or in chest wall behaviour at rest and during exercise. Retrospective analysis of pretransplant pulmonary function data of the transplanted patients (split into PF, CF and COPD) showed that their characteristics were almost identical to those of the patients with PF, CF and COPD (see online supplement).

Besides the selection of the patients (see above), the main limitation of our study is that the patients after transplantation are not identical to those before transplantation. In the online data supplement, however, it is shown that the lung function of these groups is matched. Another limitation is that exercise data are presented only during the unloaded cycling and maximal workload. This was due to the very limited exercise capacity of our patients, since half of them could only perform one level of exercise.

In conclusion, we showed that there are three distinct patterns of chronic respiratory failure in patients with PF, CF and COPD adopted by the ventilatory pump to cope with the underlying lung disease. Our data provide new evidence as to why patients with PF and, to a lesser extent, with CF are prone to respiratory failure much earlier than patients with COPD. The ventilatory pump of patients with PF and CF lacks any reserve, since coping with increasing elastic load leads to high breathing frequency. After lung transplantation, these chronic adaptations of the ventilatory pattern to advanced lung diseases are reversible and may indicate that the main contributing factor is the lung itself rather than systemic effects of the disease. We believe that our results will be helpful for optimising pulmonary rehabilitation before and after lung transplantation as well as weaning from mechanical ventilation after acute exacerbations.

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**Competing interests** None.

**Ethics approval** This study was conducted with the approval of the ethics committee of the Arztzammer of Saarlandes, Germany.

**Provenance and peer review** Not commissioned; externally peer reviewed.

**REFERENCES**