Lung function corner

Transfer coefficient of the lung for carbon monoxide and the accessible alveolar volume: clinically useful if used wisely

Case history

A 67-year-old morbidly obese female (body mass index: 46.3 kg·m\(^{-2}\)) with a history of long-term cigarette smoking (>30 pack-years) was referred from Cardiology to Respirology due to progressive dyspnoea and recent findings of extensive mosaic attenuation of the lungs on a high-resolution computed tomography (HRCT) scan (figure 1). She had been followed by Cardiology on the grounds of multivalvular disease (severe aortic stenosis and moderate mitral regurgitation), ischaemic heart disease, hypertension and hypercholesterolaemia.

The patient reported exertional dyspnoea in the past 5 years, which had worsened markedly in the past year. In fact, her dyspnoea has progressed from a previous grade of 2 according to the 1–5 Medical Research Council scale to a current grade of 4. Apart from occasional, non-productive cough she denied any other respiratory symptom. As part of her pre-operative assessment for potential transcatheter aortic valve implantation, a chest radiograph showed ill-defined, bilateral haziness which was deemed inconsistent with her current haemodynamic status. As mentioned, a subsequent chest HRCT scan (figure 1) prompted referral to the respiratory service.

Question

How can the pulmonary function testing (PFT) laboratory be helpful in guiding further investigations to uncover the cause(s) of the abnormalities observed on chest HRCT?

Answer

The mosaic pattern of lung attenuation seen in figure 1 is characterised by a patchwork of regions of differing attenuation with well-defined borders.
corresponding to the secondary pulmonary lobules [1]. As expected by the secondary lobules’ anatomy, the mosaic pattern may be due to pulmonary vascular, small airway or infiltrative lung disease [2]. Infiltrative lung disease and airway disease can be reliably differentiated by an experienced radiologist. However, pulmonary vascular disease is often misinterpreted as an airway disease [1]. Comparing inspiratory and expiratory CT scans can be helpful in indicating the presence of gas trapping secondary to small airway disease although the support for this approach comes mainly from studies involving patients with high likelihood of gas trapping, e.g. asthma, bronchiolitis obliterans and cystic fibrosis [3–5]. Thus, clinical interpretation of PFTs in the current scenario should be focused on answering the following question: is the patient’s mosaic pattern on chest HRCT more likely related to an airway- or a pulmonary vascular-centred disease?

Results of routine PFTs are shown in table 1. Spirometry was essentially within normal limits with a trend towards mild and proportional decrease in FEV1 and FVC either pre- or post-bronchodilator [6]. Body plethysmography also suggested a trend towards restriction with a borderline decrease in TLC, a high IC and a low ERV. There was no evidence of gas trapping either absolute (high RV) or relative (high RV/TLC); in fact, FRC and RV were low. The VA, as determined by methane dilution in the single-breath Tlco measurement [7], was normal-to-low in tandem with TLC, i.e. the VA/TLC ratio was within normal limits (>0.8) [8–10]. Thus, there was no significant maldistribution of ventilation [9, 10]. Of note, the haemoglobin–corrected Tlco was severely reduced as well as the Kco (Tlco/VA ratio) [11]. Inhaled bronchodilator had no significant effect on the recorded variables (table 1).

Collectively, these results indicate: an incipient restrictive ventilatory defect coupled with other findings (increased IC, decreased FRC, decreased ERV and decreased RV) which could be largely ascribed to patient’s body habitus (morbid obesity) [12]; associated with an out-of-proportion decrease in Tlco and a severe impairment in gas exchange efficiency (low Kco).

Thus, a pulmonary vascular aetiology was considered the most likely reason behind the observed mosaic pattern on the patient’s HRCT.

### Clinical follow-up

Based on the PFTs data suggesting pulmonary vascular disease and the mosaic pattern on HRCT with an enlarged pulmonary artery trunk, an urgent transthoracic echocardiogram confirmed pulmonary hypertension (PH). A ventilation/perfusion (V′/Q′) scan was requested with a specific concern of thromboembolic disease [13]; in fact, it did show multiple segmental mismatched V′/Q′ deficits. A CT pulmonary angiogram confirmed chronic thromboembolic material within dilated central pulmonary arteries. Right heart catheterisation results were consistent with pre-capillary PH (mean pulmonary arterial pressure: 39 mmHg, pulmonary arterial wedge pressure: 10 mmHg). In this context, the patient was diagnosed with chronic thromboembolic pulmonary hypertension (CTEPH) [13] and referred to the institutional PH clinic.

### Discussion

The transfer of any inspired gas with the ability of binding to haemoglobin (e.g. O2) in the red blood cells (RBCs) crossing the pulmonary capillaries depends on [14]:

- the pre-haemoglobin resistance to gas flow (literally from the mouth to the interior of the

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**Table 1** Standard pulmonary function tests pre- and post-inhaled bronchodilator

<table>
<thead>
<tr>
<th></th>
<th>Pre-bronchodilator</th>
<th>Post-bronchodilator</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spirometry</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FEV1 % pred</td>
<td>71</td>
<td>74</td>
</tr>
<tr>
<td>FVC % pred</td>
<td>75</td>
<td>74</td>
</tr>
<tr>
<td>FEV1/FVC</td>
<td>0.68</td>
<td>0.72</td>
</tr>
<tr>
<td>FEV1/SVC</td>
<td>0.64</td>
<td>0.65</td>
</tr>
<tr>
<td>FEF25–75% % pred</td>
<td>63</td>
<td>62</td>
</tr>
<tr>
<td><strong>Body plethysmography</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TLC % pred</td>
<td>78</td>
<td>81</td>
</tr>
<tr>
<td>VC % pred</td>
<td>72</td>
<td>74</td>
</tr>
<tr>
<td>IC % pred</td>
<td>128(^a)</td>
<td>121(^a)</td>
</tr>
<tr>
<td>FRC % pred</td>
<td>69(^a)</td>
<td>67(^a)</td>
</tr>
<tr>
<td>ERV % pred</td>
<td>32(^a)</td>
<td>29(^a)</td>
</tr>
<tr>
<td>RV % pred</td>
<td>62(^a)</td>
<td>68(^a)</td>
</tr>
<tr>
<td>RV/TLC</td>
<td>0.47</td>
<td>0.46</td>
</tr>
<tr>
<td><strong>Airway resistance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw % pred</td>
<td>122</td>
<td>138</td>
</tr>
<tr>
<td>sRaw % pred</td>
<td>147</td>
<td>142</td>
</tr>
<tr>
<td><strong>Gas exchange</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VA % pred</td>
<td>72</td>
<td>76</td>
</tr>
<tr>
<td>VA/TLC</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
<td>Tlco % pred</td>
<td>40(^a)</td>
<td>38(^a)</td>
</tr>
<tr>
<td>Kco % pred</td>
<td>62(^a)</td>
<td>58(^a)</td>
</tr>
</tbody>
</table>

FEV1: forced expiratory volume in 1 s; FVC: forced expiratory volume; SVC: slow vital capacity; FEF25–75%: forced expiratory flow between 25 and 75% of FVC; TLC: total lung capacity; VC: vital capacity; IC: inspiratory capacity; FRC: functional residual capacity; ERV: expiratory reserve volume; RV: residual volume; Raw: airway resistance; sRaw: specific airway resistance; VA: accessible alveolar volume; Tlco: transfer factor of the lung for carbon monoxide; Kco: transfer coefficient of the lung for carbon monoxide. \(^a\): abnormal test results (outside the 95% confidence interval).
When carbon monoxide (CO) is used instead of O₂ to assess the integrity of this complex process (haemoglobin’s affinity for CO is 230 times that of O₂), it has been shown that ~80% of the TLCO signal comes from the blood phase, i.e. the number of RBCs and/or the number of open capillary vessels (capillary volume, VC) [15]. It is therefore understandable that TLCO is considered a “window to the pulmonary microcirculation” [16]. It may also partially explain why a low TLCO is associated with increased areas of high ventilation–perfusion relationship [17]. It follows that patients with chronic obstructive pulmonary disease presenting with a low TLCO need to ventilate in excess to a given metabolic load (i.e. poor exertional ventilatory efficiency) to overcome an enlarged physiological dead space [18]. Patients with low TLCO (<50% predicted) are also at higher risk of presenting with another source of increased ventilatory stimuli: hypoxaemia [19]. Thus, a low TLCO may be associated with a high respiratory neural drive on exertion, a key correlate of exertional dyspnoea [20]. It is not surprising, therefore, that a low TLCO is an independent predictor of decreased physical activity in this patient population [21].

The clinical interpretation of TLCO, however, might be confounded by the fact that it is critically dependent on:

1) the lung volume at which it is measured and, importantly,
2) “how many” gas exchanging units at a given lung volume have received the inhaled gas mixture [22, 23].

Regarding the first point, TLCO increases as the alveoli are distended because the surface area for gas exchange increases and because the alveolar–capillary membrane may become thinner. Conversely, as the lung deflates TLCO decreases because the surface area decreases while it may become progressively thicker [24]. However, alveolar distension also compresses the lung capillaries, whereas alveolar emptying gives more space to capillary filling [25] (although this is partially compensated by a squeezing effect on the total intra-thoracic blood volume at very low lung volumes) [26]. It follows that [24–26]: from mid-lung volumes upwards, TLCO increases less than it would be expected from the increase in VA because the latter effect is partially counterbalanced by a (small) decrease in VC; and from mid-lung volumes downwards, TLCO decreases less than it would be expected from the decrease in VA because VC decreases less than the VA [23]. The final result is a curvilinear, exponential-like increase in the VC/VA ratio as the VA diminishes. Translating those concepts to TLCO measurements, they imply an essentially linear decrease in TLCO but an exponential increase in KCO (TLCO/VA) as VA decreases (figure 2) [23]. These considerations carry important messages:

- they might lead to a “pseudo-normal” KCO in a restrictive defect that decreases both TLCO and VA [27]; and
- 1 “unit” change in VA does not lead to 1 “unit” change in TLCO across all possible VA values, i.e. it is highly misleading to state that “the TLCO/VA ratio represents TLCO corrected by lung volume”.

Concerning the second point, it should be remembered that during the TLCO manoeuvre we measure only the fraction of TLC which can be accessed by the inhaled mixture (which is provided by VA), a volume that depends on how well the peripheral units connect with the large airways [10, 28]. In most healthy subjects, the VA/TLC ratio is ≥0.85 [8, 29] or ≥0.80 [9] provided that the subject performed a maximal inspiratory manoeuvre. However, in the presence of airway disease and extensive maldistribution of ventilation, VA will be a poor representation of the lungs as a whole (TLC) and VA/TLC ratio is <0.80–0.85 [28]. This might lead to a “pseudo-normal” KCO in an obstructive defect that decreases VA [27].

How to deal with these potential pitfalls in VA and KCO interpretation? We suggest the following simplified interpretation algorithm when TLCO is reduced (figure 3) [23].

When VA is normal there is a high negative predictive value for restriction (because VA is always a fraction of TLC; thus, if VA is normal so is TLC in...
The transfer coefficient of the lung for carbon monoxide and the accessible alveolar volume for the great majority of subjects [30]. If obstruction with maldistribution of ventilation were present, it would decrease $V_A$ secondary to a low $V_A/TLC$ [31]. It follows that a normal $V_A$, when associated with a low $K_{CO}$ (provided there is no anaemia or recent smoking), suggests pulmonary vascular disease (e.g., PH or vasculitis), intrapulmonary right-to-left shunting or early emphysema, i.e., mild enough to not (yet) be associated with a low $V_A/TLC$.

When $V_A$ is low the next step is to check the $V_A/TLC$ ratio.

- If the $V_A/TLC$ ratio is low (<0.8) indicating obstruction with ventilation distribution abnormalities [10, 28], the $K_{CO}$ might turn “normal”. In this scenario, no further valid inferences can be made regarding $K_{CO}$; however, if $K_{CO}$ is low despite those caveats (which, as mentioned, would otherwise tend to increase the $TLCO/V_A$ ratio), there is extensive impairment in pulmonary gas exchange efficiency, e.g., severe emphysema [32].
- If the $V_A/TLC$ ratio is normal (≥0.8), the only explanation for a low $V_A$ is a low $TLC$, i.e., restriction [30]. Thus:
  1. A high $K_{CO}$ indicates a predominance of $VC$ over $VA$ due to: a) incomplete alveolar expansion but preserved gas exchange units frequently leading to $K_{CO} > 120–140\%$ or even higher, i.e., extra-parenchymal restriction (e.g., pleural, chest wall or neuromuscular disease) [11]; b) an increase in pulmonary blood flow from areas of diffuse (pneumonectomy) or localised (local destructive lesions/atelectasis) loss of gas exchange units to areas with preserved parenchyma frequently leading to more modest increases in $K_{CO}$ (although a high $K_{CO}$ can also be seen with normal or near-normal $V_A$ when there is increased pulmonary blood flow or redistribution such as left-to-right shunt and asthma); and c) extra-vascular haemoglobin, i.e., alveolar haemorrhage.
  2. A low $K_{CO}$ points towards intra-parenchymal restriction with impaired gas exchange efficiency as in some interstitial lung diseases (ILD) [33].
  3. A normal $K_{CO}$ is consistent with intra-parenchymal restriction with preserved $K_{CO}$. This is the most common finding in patients with HRCT abnormalities showing a pattern consistent with idiopathic interstitial pneumonia [33]. Thus, a normal $K_{CO}$ should not be misinterpreted as indicative of “no ILD” [34, 35]. In this context, a normal $K_{CO}$ may either indicate that the main mechanism underlying the low $TLC$ is loss of lung volume (e.g., fibrotic ILD) or the low $V_A$ led to a normalisation of $K_{CO}$ due to the curvilinear increase in $K_{CO}$ as $V_A$ decreases (figure 2).

Figure 3: A simplified algorithm for the differential diagnosis of a low $TLC$ taking into consideration the potential pitfalls involved in interpretation of the accessible $V_A$ and $K_{CO}$. Symbols ↑, ↓ and ↔ represent values above, below and within the normal range, respectively. See the text for further elaboration.
Owing to the trend for $K_{CO}$ to be higher than $T_{LCO}$ regardless the underlying reason(s), the severity of functional impairment should always be gradated based on $T_{LCO}$ based on the European Respiratory Society recommendations: mild (less than lower limit of normal, but above 60% predicted according to the recently published Global Lung Initiative equations [36]), moderate (40–60% predicted) and severe (>40% predicted) [6].

In the present case, a low $V_{A}$ but normal $V_{A}/TLC$ (coupled with the absence of obstruction on spirometry, gas trapping or high specific airway resistance) is not consistent with maldistribution of ventilation due to small airway disease. Thus, $V_{A}$ decreased in proportion to a low TLC, i.e., secondary to the patient’s morbid obesity and/or to the known trend for CTEPH patients to present with mild restriction due to microatelectasis and fibrotic changes [37]. As shown in figure 2, $K_{CO}$ should increase as $V_{A}$ decreases if there was no impairment in gas exchange efficiency; in fact, this is one of the justifications as to why obesity is associated with a high $K_{CO}$ [38]. It follows that the only plausible explanation for a low $K_{CO}$ in the present case is a low VC, i.e., a pulmonary vascular disease. Some key interpretative issues regarding $T_{LCO}$ and its derived measurements are provided in table 2.

### Table 2  Key recommendations to avoid frequent pitfalls in the interpretation of $T_{LCO}$, $K_{CO}$ and $V_{A}$ in clinical practice

<table>
<thead>
<tr>
<th>Recommendation</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Always rule out anaemia and recent smoking (i.e. CO inhalation) as a cause for a low $T_{LCO}$.</td>
<td>Decreases the number of haemoglobin sites available for CO binding and higher CO back-pressure, respectively.</td>
</tr>
<tr>
<td>The $T_{LCO}/V_{A}$ ratio does not represent “$T_{LCO}$ corrected by lung volume”. To avoid confusion and misinterpretation, $K_{CO}$ should always be used instead of $T_{LCO}/V_{A}$.</td>
<td>A one unit change in $V_{A}$ does not necessarily lead to one unit change in $T_{LCO}$.</td>
</tr>
<tr>
<td>A “preserved” $K_{CO}$ should never be interpreted as indication of no major pulmonary pathology.</td>
<td>In both obstructive and restrictive diseases $V_{A}$ may decrease out-of-proportion to $T_{LCO}$ leading to a “pseudo-normal” $K_{CO}$.</td>
</tr>
<tr>
<td>The first step in the interpretation of $K_{CO}$ in the presence of a low $V_{A}$ is to check the $V_{A}/TLC$ ratio.</td>
<td>If low (&lt;0.8) there is maldistribution of ventilation, frequently leading to a “pseudo-normal” $K_{CO}$.</td>
</tr>
<tr>
<td>Rule out submaximal inspiration (inspired volume should be at least 85% of the largest VC) as the cause of a low $V_{A}$ before interpreting a high $K_{CO}$.</td>
<td>Due to the marked increase in $K_{CO}$ as $V_{A}$ decreases, relatively small decrements in the latter has a major impact on $K_{CO}$.</td>
</tr>
<tr>
<td>Always grade the functional impairment based on decrease in $T_{LCO}$ not in $K_{CO}$.</td>
<td></td>
</tr>
</tbody>
</table>

### Key points

- Clinical interpretation of the $T_{LCO}$ frequently benefits from associated analysis of the accessible $V_{A}$, $V_{A}/TLC$ ratio and the diffusion coefficient ($K_{CO}$).
- The $T_{LCO}/V_{A}$ ratio ($K_{CO}$) should not be erroneously interpreted as “$T_{LCO}$ corrected by lung volume” because a one unit change in $V_{A}$ does not lead to one unit change in $T_{LCO}$ across all possible $V_{A}$ values.
- Preserved $V_{A}$ and a low $K_{CO}$ (provided the absence of anaemia or recent smoking) suggests pulmonary vascular disease, intrapulmonary right-to-left shunting or early emphysema.
- A low $V_{A}$ in the presence of a normal $V_{A}/TLC$ ratio suggests restriction: a low $K_{CO}$ points towards intra-parenchymal restriction with impaired gas exchange efficiency whereas a high $K_{CO}$ is consistent with extra-parenchymal restriction.
- A low $V_{A}$ in the presence of a low $V_{A}/TLC$ ratio indicates obstruction with ventilation distribution abnormalities: whereas a preserved $K_{CO}$ is not amenable to interpretation, a low $K_{CO}$ indicates extensive impairment in pulmonary gas exchange efficiency, e.g. severe emphysema.
- A normal $K_{CO}$ should not be used to rule out major pulmonary pathology, particularly when $V_{A}$ is reduced.
Self-evaluation questions

In each of the following patients, please indicate which is the most likely underlying diagnosis which could explain the observed abnormalities (indicated by a * symbol).

1.

<table>
<thead>
<tr>
<th>TLC % pred</th>
<th>TLCO % pred</th>
<th>VA % pred</th>
<th>VA/TLC</th>
<th>Kco % pred</th>
</tr>
</thead>
<tbody>
<tr>
<td>132 *</td>
<td>52 *</td>
<td>64 *</td>
<td>0.56 *</td>
<td>87</td>
</tr>
</tbody>
</table>

a) Idiopathic PH  
b) Neuromuscular disease  
c) Emphysema  
d) Asthma  
e) ILD

2.

<table>
<thead>
<tr>
<th>TLC % pred</th>
<th>TLCO % pred</th>
<th>VA % pred</th>
<th>VA/TLC</th>
<th>Kco % pred</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 *</td>
<td>68 *</td>
<td>44 *</td>
<td>0.97</td>
<td>145 *</td>
</tr>
</tbody>
</table>

a) Idiopathic PH  
b) Neuromuscular disease  
c) Emphysema  
d) Asthma  
e) ILD

3.

<table>
<thead>
<tr>
<th>TLC % pred</th>
<th>TLCO % pred</th>
<th>VA % pred</th>
<th>VA/TLC</th>
<th>Kco % pred</th>
</tr>
</thead>
<tbody>
<tr>
<td>91</td>
<td>54 *</td>
<td>82</td>
<td>0.86</td>
<td>64 *</td>
</tr>
</tbody>
</table>

a) Idiopathic PH  
b) Neuromuscular disease  
c) Emphysema  
d) Asthma  
e) ILD

4.

<table>
<thead>
<tr>
<th>TLC % pred</th>
<th>TLCO % pred</th>
<th>VA % pred</th>
<th>VA/TLC</th>
<th>Kco % pred</th>
</tr>
</thead>
<tbody>
<tr>
<td>69 *</td>
<td>44 *</td>
<td>67 *</td>
<td>0.93</td>
<td>58 *</td>
</tr>
</tbody>
</table>

a) Idiopathic PH  
b) Neuromuscular disease  
c) Emphysema  
d) Asthma  
e) ILD

5.

<table>
<thead>
<tr>
<th>TLC % pred</th>
<th>TLCO % pred</th>
<th>VA % pred</th>
<th>VA/TLC</th>
<th>Kco % pred</th>
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</thead>
<tbody>
<tr>
<td>107</td>
<td>112</td>
<td>99</td>
<td>0.82</td>
<td>129 *</td>
</tr>
</tbody>
</table>

a) Idiopathic PH  
b) Neuromuscular disease  
c) Emphysema  
d) Asthma  
e) ILD
Affiliations

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This article is dedicated to Dr. J. Michael B. Hughes and Dr. Neil B. Pride (National Heart and Lung Institute, Imperial College, Hammersmith campus, London, UK) whose work has been instrumental to advance the clinical interpretation of TLCO and its derived measurements.

Conflict of interest

None declared.

References

Suggested answers

1. c. Moderately reduced TLco. Low Va is associated with a low Va/TLC and a high TLC indicating extensive ventilation distribution abnormalities in the context of an obstructive airway disease. Of note, despite low Va/TLC, Kco is reduced indicating extensive impairment in gas exchange efficiency. Collectively, emphysema is the most likely explanation for these findings.

2. b. Mildly reduced TLco. Markedly low Va is associated with an equally low TLC and preserved Va/TLC. Thus, Kco is supra-normal. Collectively, these results are in line with extra-parenchymal restriction. Given the options available, neuromuscular disease is the most likely explanation for these findings (differentials being pleural and chest wall disease).

3. a. Moderately reduced TLco. Va, TLC and Va/TLC are within normal limits. Thus, Kco is reduced. Collectively, the results are in line with impaired intrapulmonary gas exchange efficiency in the absence of restriction or significant airway disease. Given the options available, idiopathic PH is the most likely explanation for these findings (differentials being other pulmonary vascular diseases and right-to-left shunt).

4. e. Moderate-to-severe impairment in TLco. Low Va is associated with an equally low TLC and preserved Va/TLC. Kco is also reduced. Collectively, the results are in line with intra-parenchymal restriction. Given the options available, ILD (with impaired gas exchange efficiency) is the most likely explanation for these findings.

5. d. Preserved TLco but supra-normal Kco in the context of normal TLC. Given the options available, asthma is the most likely explanation for these findings (differential being left-to-right shunt).


