Single lung alveolar volume and gas transfer: effect of expansion of the other lung

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Abstract

Background — Temporary occlusion of one mainstem bronchus permits measurement of single lung function. A previous study suggested that the volume at which one lung is occluded may influence the expansion of the other. The effect of ipsilateral occlusion volume on the contralateral effective alveolar volume ($V_A,_{E,F}$), index volume ($V_{I,SL}$), single breath estimated residual volume (RVSB,SL), carbon monoxide (CO) transfer ($TLCO,_{SL}$) and transfer coefficient ($KCO,_{SL}$) has been examined.

Methods — Single breath measurements of CO transfer were made in duplicate in 12 healthy subjects aged 19–44 years, without and during occlusion of one mainstem bronchus by a balloon at RV and at total lung capacity (TLC).

Results — Mean $V_A,_{E,F,SL}$, $V_{I,SL}$, and $TLCO,_{SL}$ were lower during occlusion at RV than during occlusion at TLC (2.84 v 3.26 l; 2.18 v 2.54 l; and 4.70 v 5.51 mmol/kPa/min respectively). RVSB,SL was independent of occlusion volume and $KCO,_{SL}$ not different from the $KCO$ of both lungs ($KCO,_{BL}$). Single lung volumes during occlusion at TLC were fairly reproducible and were, except for $KCO,_{SL}$, approximately half the values for both lungs. During occlusion at RV the second $TLCO,SL$ and $KCO,SL$ were lower than the first.

Conclusions — Occlusion of one lung permits reliable determinations of gas transfer indices of the other, provided the lung is occluded at TLC. Occlusion at RV significantly reduces $V_A,_{E,F,SL}$, and hence $TLCO,_{SL}$, but does not affect $KCO,_{SL}$ of the other lung.

(Thorax 1994;49:1238–1242)

In a previous study we occluded one mainstem bronchus at total lung capacity (TLC) and measured static volumes of the other lung by gas dilution.¹ The residual volume (RV) of the latter was higher than expected, suggesting that the hyperinflated occluded lung prevented the emptying of the other. This finding made us wonder if unilateral occlusion of a deflated lung — that is, at RV — could affect the expansion of the other lung. To further explore the occlusion technique, but avoid lasting occlusion at RV, we used the single breath carbon monoxide (CO) transfer test² to study the role of unilateral occlusion volume. This method includes the inhalation from RV to TLC of a test gas containing helium and carbon monoxide. The dilution of helium during breathing permits calculation of the effective alveolar volume ($V_A,_{E,F}$), which in health is similar to TLC,¹ and which is a prerequisite for the calculation of the transfer factor (TLCO).

Intra-individual variations in preinspiratory lung volume before the test gas is inhaled have no effect on gas transfer.² Variations in end inspiratory volume during breathing, however, are positively related to TLCO.⁶,⁸ Furthermore, the transfer coefficient ($KCO$), or $TLCO/V_A,_{E,F}$, is inversely related to end inspiratory volume.⁹,¹⁰ If unilateral occlusion at RV decreases TLC — that is, $V_A,_{E,F}$ of the other lung — $TLCO$ of that lung should also decrease and $KCO$ increase. In contrast, occlusion at TLC should not affect gas transfer even if RV of the other lung increases. The purpose of this study was (1) to measure single breath gas transfer of one lung during occlusion of the other, and (2) to test the hypothesis that the volume at which occlusion takes place determines the filling of the other lung.

Methods

SUBJECTS

Seven male and five female healthy volunteers aged 19–44 years, smokers and non-smokers, participated in this study. They had no history of respiratory or cardiac disease or recent airway infection, nor had they any clinical signs of airways obstruction. Their ventilatory lung function was within normal limits as determined by spirometry on the day of investigation.¹¹ One additional woman was examined but excluded due to persistent cough during the initial bronchoscopy. Each subject was carefully informed about the purpose and the content of the study, both verbally and in writing. All gave written informed consent to participate. The study was approved by the Regional Health Area ethical committee.

AIRWAY OCCLUSION

The mainstem bronchus was occluded by the inflatable balloon of an 80 cm long Fogarty venous thrombectomy catheter, size 8/10 French (American Edwards Laboratories, Santa Ana, California, USA). The balloon had a maximum diameter of 19 mm and a maximum capacity of 4 ml. The catheter was advanced transnasally into the mainstem bronchus under guidance of a paediatric fiberoptic bronchoscope (Olympus BF OC10) during topical anaesthesia with nebulised oxybu-
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Single lung and were in they before also when with mainstem bronchus of one lung the RV; \( (a) \) lung was mouth, \( \text{moglobin} \) PROTOCOL tomical studied. 13 helium was litres BTPS and exclusion and \( (b) \) lung was recorded. \( \text{atropine, diazepam, Procaine.} \) \( \text{bronchus,} \) the catheter with deflated balloon was fixed to the nostril, the bronchroscope removed, and the subjects placed in another chair in front of the transfer test apparatus. At that time they had been seated for at least 30 minutes.

GAS TRANSFER MEASUREMENTS
The single breath transfer factor was measured with a Gould automated system 2400 (Sensormedics BV, Bilthoven, The Netherlands) and according to guidelines recommended by the European Community for Coal and Steel (ECCS).11 The test gas mixture was composed of 0-29% carbon monoxide, 9-41% helium, 19-3% oxygen, and a balance of nitrogen. It was inhaled after a maximal expiration and allowed to dilute and/or diffuse during breath-holding in maximal inspiration. The first 750 ml of the expire was discarded and the next 750 ml sampled in a bag and analysed for carbon monoxide and helium. \( V_{A,eff} \) was calculated from the corrected dilution of helium and the inspired volume (Vi). Anatomical (see below) and instrumental dead space (85 ml) were subtracted from Vi before \( V_{A,eff} \) was calculated. The concentration of expired helium was divided by 1-05 to correct for absorption of carbon dioxide before helium analysis. The single breath estimate of RV (RVSB) was defined as \( V_{A,eff} \) minus Vi. \( V_{A,eff} \) in litres BTPS was used to calculate TLCO, and KCO was calculated as TLCO/\( V_{A,eff} \). Anatomical deadspace was 150 ml without occlusion and 115 ml when one lung was studied.13 Breathholding was preset to 10 seconds, and the effective duration of breathholding derived as recommended.14 Haemoglobin and carboxyhaemoglobin levels were not measured. The subjects were studied at sea level. Reference values were those of ECCS.12

STUDY PROTOCOL
Whole lung function, as measured at the mouth, was recorded in three consecutive circumstances: (a) with the balloon deflated; (b) with mainstem bronchus of one lung occluded at RV; and (c) with the same lung occluded at TLC. To minimise the effect of volume history15 the subjects made two or three tidal breaths, also when one lung was occluded, before they exhaled to RV and rapidly breathed in the test gas. In all circumstances measurements were made in duplicate with a five minute interval between each replicate. The mainstem bronchus was never occluded for more than 30 seconds at a time. The subjects remained seated during the whole session. Oxygen saturation was recorded throughout the procedure with a pulse oximeter (Minolta Pulsox-7).

RANDOMISATION AND DATA ANALYSIS
The lung to be occluded was selected at random for each subject, but we had already decided to examine six right and six left lungs. The sequence of measurement when the mainstem bronchus was occluded at either TLC, RV, or not at all was randomised for each subject according to a complete block design. The statistical package SPSS (version 4.0) was used for data entry and analysis. The measurement error was defined as the standard deviation of a single determination (standard deviation of the difference between duplicate values divided by the square root of 2), and repeatability as the coefficient of variation. Mean values were compared with the two tailed paired and two sample t test, and considered to be significantly different if the \( p \) value was <0.05. Relations between continuous variables were examined by Pearson's correlation coefficient. If systematic differences between replicates were found, the value of the first was used for further analysis, otherwise the average of duplicate values was used.

Results
PRECISION
Table 1 shows that without occlusion and during occlusion at TLC no systematic differences between replicates were found except that the second RVSB,BL was lower than the first (1-27 \( v \) 1-341, \( p<0.01 \)). In contrast, when occlusion took place at RV, the second replicates of RVSB,SL, TLCO,SL, and KCO,SL of the non-occluded lung were significantly lower than the first. The smaller second RVSB,SL was accompanied by a somewhat larger Vi,SL, making the first and second \( V_{A,eff},SL \) identical. Table 1 also shows that the measurement errors of single lung variables did not differ much from those of the whole lung, but that the coefficient of variation was twice as large.

COMPARISON BETWEEN SINGLE AND BOTH LUNGS
The individual values of TLCO (average of replicates) for both lungs and for one lung during occlusion at TLC are listed in table 2. The mean TLCO for both lungs was 11-00, and for a single lung 5-36 mmol/kPa/min. There was no difference between the absolute values of the right and left lung. However, the ratio of the right TLCO,SL to TLCO,BL was significantly larger than that of the left to the whole lung (0-55 \( v \) 0-44, \( p<0.05 \), two sample t test). The table also shows that the ratio of the right \( V_{A,eff},SL \) to \( V_{A,eff},BL \) was larger than that of the left to the whole lung (0-57 \( v \) 0-50, \( p<0.05 \)). There was a correlation between the ratio of
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Table 1  Duplicate group mean values and measurement error of whole and single lung gas transfer components in 12 healthy volunteers

<table>
<thead>
<tr>
<th>Occlusion volume</th>
<th>First test</th>
<th>Second test</th>
<th>SEt</th>
<th>p</th>
<th>SDt</th>
<th>CV (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>VA, EFF, BL</td>
<td>6.22</td>
<td>6.20</td>
<td>0.032</td>
<td>NS</td>
<td>0.08</td>
</tr>
<tr>
<td>None</td>
<td>VI, BL</td>
<td>4.88</td>
<td>4.92</td>
<td>0.029</td>
<td>NS</td>
<td>0.07</td>
</tr>
<tr>
<td>None</td>
<td>RV, BL</td>
<td>1.34</td>
<td>1.27</td>
<td>0.021</td>
<td>&lt;0.01</td>
<td>NA</td>
</tr>
<tr>
<td>None</td>
<td>TLC</td>
<td>10-91</td>
<td>11-09</td>
<td>0.196</td>
<td>NS</td>
<td>0.48</td>
</tr>
<tr>
<td>None</td>
<td>KCO,BL</td>
<td>1-76</td>
<td>1-78</td>
<td>0.032</td>
<td>NS</td>
<td>0.08</td>
</tr>
<tr>
<td>TLC</td>
<td>VA, EFF, SL</td>
<td>3-26</td>
<td>3-26</td>
<td>0.041</td>
<td>NS</td>
<td>0.11</td>
</tr>
<tr>
<td>TLC</td>
<td>VI, SL</td>
<td>2-54</td>
<td>2-54</td>
<td>0.036</td>
<td>NS</td>
<td>0.09</td>
</tr>
<tr>
<td>TLC</td>
<td>RV, BL</td>
<td>0-72</td>
<td>0-72</td>
<td>0.020</td>
<td>NS</td>
<td>0.05</td>
</tr>
<tr>
<td>TLC</td>
<td>TLCO, SL</td>
<td>5-51</td>
<td>5-20</td>
<td>0.031</td>
<td>NS</td>
<td>0.04</td>
</tr>
<tr>
<td>TLC</td>
<td>KCO, SL</td>
<td>1-69</td>
<td>1-59</td>
<td>0.054</td>
<td>NS</td>
<td>0.07</td>
</tr>
<tr>
<td>RV</td>
<td>VA, EFF, SL</td>
<td>2-84</td>
<td>2-84</td>
<td>0.044</td>
<td>NS</td>
<td>0.11</td>
</tr>
<tr>
<td>RV</td>
<td>VI, SL</td>
<td>2-14</td>
<td>2-23</td>
<td>0.052</td>
<td>NS</td>
<td>0.13</td>
</tr>
<tr>
<td>RV</td>
<td>RV, BL</td>
<td>0-70</td>
<td>0-62</td>
<td>0.037</td>
<td>&lt;0.05</td>
<td>NA</td>
</tr>
<tr>
<td>RV</td>
<td>TLC, BL</td>
<td>4-70</td>
<td>4-18</td>
<td>0.186</td>
<td>&lt;0.02</td>
<td>NA</td>
</tr>
<tr>
<td>RV</td>
<td>KCO, SL</td>
<td>1-65</td>
<td>1-46</td>
<td>0.047</td>
<td>&lt;0.005</td>
<td>NA</td>
</tr>
</tbody>
</table>

VA, EFF = effective alveolar volume; VI = inspired volume; RV, BL = single breath residual volume; TLC = transfer factor; KCO = transfer coefficient; SEt = standard error of the difference between means; SDt = standard deviation of a single determination (measurement error); CV = coefficient of variation; NS = not significant; NA = not applicable; BL = both lungs; SL = single lung. Volumes are expressed in litres BTPS, TLCO in mmol/min/kPa, and KCO in mmol/min/kPa/l.

Table 2  Predicted and observed transfer factor (TLCO) of both lungs and of a single lung during occlusion at TLC, and the ratios of single to both lung transfer factor and effective alveolar volume in 12 healthy volunteers

<table>
<thead>
<tr>
<th>Subject no.</th>
<th>Examinated lung</th>
<th>Predicted TLCO, BL</th>
<th>Observed TLCO, BL</th>
<th>Observed TLCO, SL</th>
<th>Ratio TLCO, SL/TLCO, BL</th>
<th>Ratio VA, EFF, SL/VACO, BL</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Right</td>
<td>9-00</td>
<td>6-15</td>
<td>4-37</td>
<td>0-71</td>
<td>0-68</td>
</tr>
<tr>
<td>6</td>
<td>Left</td>
<td>12-88</td>
<td>15-00</td>
<td>8-79</td>
<td>0-59</td>
<td>0-57</td>
</tr>
<tr>
<td>7</td>
<td>Right</td>
<td>10-30</td>
<td>12-10</td>
<td>6-01</td>
<td>0-50</td>
<td>0-53</td>
</tr>
<tr>
<td>8</td>
<td>Right</td>
<td>10-01</td>
<td>7-95</td>
<td>4-49</td>
<td>0-56</td>
<td>0-52</td>
</tr>
<tr>
<td>10</td>
<td>Right</td>
<td>11-86</td>
<td>11-05</td>
<td>5-44</td>
<td>0-49</td>
<td>0-55</td>
</tr>
<tr>
<td>12</td>
<td>Right</td>
<td>9-00</td>
<td>9-40</td>
<td>4-34</td>
<td>0-46</td>
<td>0-55</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td></td>
<td>10-28 (3-15)</td>
<td>5-57 (1-72)</td>
<td>0-55 (0-09)</td>
<td>0-57 (0-06)</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations and units as in table 1.

EFFECT OF OCCLUSION VOLUME
When one lung was occluded at RV the mean values of VA, EFF, SL, VI, SL, and TLCO, SL of the other were significantly lower (p<0.001) than the values obtained during occlusion at TLC (2.84 v 3.26, 2.18 v 2.54, and 4.70 v 5.51 mmol/min/kPa/min, respectively) (table 1). The lower VA, EFF, SL during occlusion at RV was not accompanied by an increase in KCO, SL, nor was there any effect of occlusion volume on RVBS, SL. There was no significant difference between KCO, BL and the two KCO, SL values (table 1, 3rd column). Some subjects noticed an unpleasant feeling in their chest at extreme lung volumes. On three occasions (of 48 in total) the oxygen saturation fell below 90%.

Discussion
The airway occlusion technique has been described in detail in a previous paper,1 which also contains references to earlier studies on unilateral lung function, in particular bronchospirometry.16 The latter was used when gas transfer of a single lung was measured for the first time.2 In that study the sum of the right and left TLCO, SL was lower than the value for both lungs. Subsequent investigators have applied bronchospirometry and the steady state method and have shown that single lung gas transfer of both healthy and diseased lungs correlated well with the ventilation to each lung.17 18 In contrast, unilateral pulmonary blood flow had to decrease considerably to affect differential gas transfer.18

In this study we occluded the mainstem bronchus on one side at both extreme lung volumes, just before the test gas was inhaled. When one lung was occluded at TLC the mean TLCO, SL and volumes of the other were approximately half the values of both lungs. During occlusion at RV three of the volume-dependent properties of the ventilating lung – VI, SL, VA, EFF, SL, and TLCO, SL – were significantly lower than during occlusion at TLC. RVBS, SL was independent of occlusion volume, while occlusion did not affect KCO at all. Repeat measurements within a few minutes gave significantly lower values for TLCO, SL and KCO, SL during occlusion at RV.

The lower VA, EFF, SL during occlusion at RV was almost entirely due to the reduced VI, SL. The difference in VI, SL at the two occlusion volumes (mean 0.36 l) was too large to be explained by a difference in blood volume in the ventilating lung, nor could it be caused by pain during inspiration as this was felt by
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The technical assistance of Inger Hem, Else-Margrethe Blix and Christin Hommen is highly appreciated. The study was supported financially by a grant from Glaxo Norway AS.


10 Lipscomb DJ, Patel K, Hughes JMB. Interpretation of increases in the transfer coefficient for carbon monoxide (TL\textsubscript{CO}VA or KCO). *Thorax* 1978;33:728-33.


