Influence of breath holding at total lung capacity on maximal expiratory flow measurements

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Summary

1. Forced exhalations performed from volumes below total lung capacity, so-called partial expiratory flow-volume curves, are suggested to be more sensitive in detecting airways bronchoconstriction than maximal expiratory flow-volume curves begun at total lung capacity.

2. In eight healthy men both maximal and partial expiratory flow-volume curves were measured where breath was held at total lung capacity or 70% of vital capacity respectively, for either 0 or 15 s before performing the forced exhalation. An histamine aerosol was used to provoke bronchoconstriction.

3. The results showed that the 15 s breath hold caused greater reduction in expiratory flow rates after histamine for both maximal and partial expiratory flow-volume curves than either manoeuvres performed with no breath hold.

4. A breath hold of 15 s at total lung capacity appeared to make the maximal expiratory flow-volume curve as sensitive as a partial expiratory flow-volume curve in detecting the response to histamine as well as providing measurements of forced expiratory volume in 1 s and vital capacity. Forced spirometry after a 15 s breath hold at total lung capacity therefore provides an easy and sensitive technique for detecting bronchoconstriction.

Key words: maximal expiratory flow-volume curve, partial expiratory flow-volume curve, breath holding, airways obstruction.

Introduction

Spirometry is commonly used to assess airways obstruction. An objection to the method is that it involves a preceding full inhalation, which may reduce airway smooth muscle tone (Green & Mead, 1974). Indeed, a full inhalation to total lung capacity (TLC) can diminish experimentally induced bronchoconstriction (Nadel & Tierney, 1961) and may reduce total pulmonary resistance even in the absence of increased airway tone (Vincent, Knudson, Leith, Macklem & Mead, 1970). The full inhalation preceding spirometry may therefore obscure small degrees of airways obstruction.

To avoid the influence of preceding volume history, Frank and associates suggested that forced exhalations should be begun at volumes well below TLC so as to be more representative of the airways in their tidal breathing range of lung volumes (Frank, Amdur, Worcester & Whittenberger, 1962). Such partial expiratory manoeuvres may be more sensitive in detecting airways obstruction than maximal expiratory manoeuvres begun from TLC (Bouhuys, Hunt, Kim & Zapletal, 1969). They have not, however, gained widespread acceptance as partial expiratory flow-volume curves are difficult to obtain from untrained subjects and do not simultaneously provide measurements of forced expiratory volume in 1 s (FEV$_{1.0}$), vital capacity (VC) or peak expiratory flow rates, which are customarily used to assess lung function.

It is possible, however, that a forced exhalation may be begun from TLC and yet still avoid the changes in airway tone associated with such a full inhalation. Reduction in airway tone, presumably a result of mechanical stretch which occurs on going to TLC, can be re-established after a brief
period of breath holding in mid-vital capacity range of lung volume (Green & Mead, 1974). Such a restoration of airway tone may also occur during breath holding at volumes close to TLC, once active stretching of the airways has ceased.

We have tested this possibility in man by using both maximal expiratory flow–volume curves begun from TLC and partial expiratory flow–volume curves begun from 70% of vital capacity, where breath was held for either 0 or 15 s before forcible exhalation.

Methods

Eight normal men were recruited: four were smokers and four non-smokers. None had asthma nor previous history of respiratory disease. Forced expiratory flow–volume curve measurements were obtained by using a dry spirometer (Ohio 840) from which flow and volume signals were analysed on-line by a minicomputer (Data General Nova IIA). The computer, running under a Fortran IV program, sampled digital flow and volume signals at 200 Hz. Sampling began and stopped when expiratory flow rates exceeded or were less than 0·2 litre/s. Where appropriate from each exhalation the following variables were measured: flow at 50 and 25% of VC, mean flow between 60 and 20% of VC, peak expiratory flow rate, FEV₁₀ and VC matching flow–volume curves at TLC. A permanent record of flow–volume curves was stored in digital form for later display. Maximal forced exhalations were performed either immediately after a full inhalation or after breath holding for 15 s at TLC. A form of partial forced exhalation was adopted, which had been used earlier to assess the influence of time on flow–volume curves (Green & Mead, 1974) and involved an initial full inhalation to TLC, then a slow exhalation to 70% of each subject’s VC when immediately, or after breath holding for 15 s, a forced exhalation was performed.

The subjects performed each of these four types of forced expiratory manoeuvres before and after breathing air/diluent or air/histamine mist from a Wright’s nebulizer for 2 min. Each subject therefore performed eight separate studies in which three replicates of one type of forced exhalation manoeuvre was performed before, and then again after, inhalation of either water or histamine mists, thus providing an internal control for the influence on flow–volume curves of breathing from a nebulizer. On every occasion histamine was used each subject inhaled the same dose of histamine hydrochloride in diluent, which on previous experimentation had caused airways obstruction (doses ranging from 2 to 4 log μmol of histamine).

By using an 8 × 8 latin square experimental design to randomize the order of the different forced exhalations, and whether or not histamine or water was inhaled, our eight subjects, on separate afternoons, underwent the eight studies. This enabled each forced exhalation manoeuvre to be tested both against water and histamine. Analysis of variance was used to assess the effects of water/histamine and the different types of forced exhalations on the variables measured from the flow–volume areas. To contrast mean values the least significant difference (Armitage, 1971) at a 5% level of significance was calculated so that differences between groups of means, which are significant at this level, could be picked out by eye.

Results

Flow rates from the partial expiratory manoeuvres before either water or histamine was inhaled were significantly lower than those measured after

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<table>
<thead>
<tr>
<th>Forced exhalation</th>
<th>Breath hold (s)</th>
<th>Expiratory flow (l/s)</th>
<th>(Vital capacity %)</th>
<th>Forced expired volume in 1s (l)</th>
<th>Peak expiratory flow (l/s)</th>
<th>Vital capacity (l)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>25%</td>
<td>50%</td>
<td>60–20%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partial from</td>
<td>0</td>
<td>1·83</td>
<td>4·30</td>
<td>2·84</td>
<td>(0·09)</td>
<td>(0·06)</td>
</tr>
<tr>
<td>70% of VC</td>
<td>15</td>
<td>1·67</td>
<td>3·67</td>
<td>2·53</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Maximal from</td>
<td>0</td>
<td>2·10</td>
<td>4·58</td>
<td>3·17</td>
<td>4·36</td>
<td>11·18</td>
</tr>
<tr>
<td>TLC</td>
<td>15</td>
<td>1·90</td>
<td>4·28</td>
<td>2·94</td>
<td>4·31</td>
<td>10·28</td>
</tr>
</tbody>
</table>
Influence of breath holding at total lung capacity on spirometry

Discussion

Maximum expiratory flow rates during forced exhalations are largely determined by airway calibre and lung elastic-recoil pressure (Mead, Turner, Macklem & Little, 1967; Pride, Permutt, Riley & Bromberger-Barnea, 1967). A full inhalation to TLC can reduce airway tone and thus increase airway calibre (Nadel & Tierney, 1961; Bouhuys et al., 1969; Green & Mead, 1974) and may also increase lung elastic-recoil pressure (Marshall & Widdicombe, 1961; Sharp, Johnson, Goldberg & Vanlith, 1976). Both adaptions resulting from a full inhalation might therefore be expected to increase expiratory flow rates, which are therefore no longer similar to those that would have been obtained had the exhalation started from a tidal breathing range of lung volume (Frank et al., 1962).

However, the reduced airway tone after a full inhalation is only a temporary phenomenon (Green & Mead, 1974). Similarly the increased elastic recoil associated with larger lung volumes may in part be reduced once the active inflation has ceased, by means of stress relaxation (Marshall & Widdicombe, 1961; Hughes, May & Widdicombe, 1969). Therefore, breath holding at TLC or the time delay measured during the slow exhalation to 70% of VC in the partial forced exhalation, some 5–6 s in most subjects, would be expected to result in lower expiratory flow rates, which are therefore no longer similar to those that would have been obtained had the exhalation started from a tidal breathing range of lung volume (Frank et al., 1962).

In contrast, histamine significantly reduced expiratory flow rates in all types of exhalation (Fig. 1 and Table 2). The VC in partial exhalations with a 15 s breath hold was also significantly reduced by histamine, but not with the other manoeuvres (Table 2). The reduction in expiratory flow rates induced by histamine was significantly less for exhalations performed immediately from TLC whereas greater reductions in flow rates with histamine were observed for partial exhalations with either a 0 or 15 s breath hold and for maximal exhalations when breath was held for 15 s at TLC, between which there were no significant differences (Table 2). Furthermore FEV$_{1.0}$ and peak expiratory flow rates were lower after histamine when measured from maximal exhalation with a 15 s breath hold than from maximal exhalations with a 0 s breath hold, although not significantly so (Table 2).

**Table 2. Mean percentage change in expiratory flow rates, forced expired volume and vital capacity after histamine inhalation**

The mean change in expiratory flow rates, FEV$_{1.0}$ and VC after histamine for each type of forced exhalation, expressed as the percentage reduction from mean pre-histamine control values.

<table>
<thead>
<tr>
<th>Forced exhalation</th>
<th>Breath hold (s)</th>
<th>Expiratory flow (Vital capacity %)</th>
<th>After histamine (% change)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>25%</td>
<td>50%</td>
</tr>
<tr>
<td>Partial from</td>
<td>0</td>
<td>−18·0</td>
<td>−16·0</td>
</tr>
<tr>
<td>70% of VC</td>
<td>15</td>
<td>−18·0</td>
<td>−18·0</td>
</tr>
<tr>
<td>Maximal from</td>
<td>0</td>
<td>−13·4*</td>
<td>−11·7*</td>
</tr>
<tr>
<td>TLC</td>
<td>15</td>
<td>−20·0</td>
<td>−16·8</td>
</tr>
</tbody>
</table>

* Significantly different from values of the other expiratory manoeuvres ($P < 0.05$).
was inhaled, expiratory flow rates from the partial expiratory flow-volume curves and from the maximal expiratory flow-volume curves after a 15 s breath hold at TLC were comparably lower than the standard maximal expiratory flow-volume curves performed without a delay at TLC. This observation may well reflect a restoration of airway tone, and stress relaxation occurring during the delay in these expiratory manoeuvres before forced exhalation. Some workers have suggested, however, that such delays could simply reduce expiratory effort and so influence the flow-volume curve (Sobol & Emirgil, 1964; Clement & Van De Woestijne, 1971), although this seems highly unlikely as reduced expiratory effort could not account for reduced flow rates seen at 25% of VC as the flow-volume curve is considered independent of effort at such volumes.

Inhalation of histamine solution as a mist principally increases bronchial smooth muscle tone (Sellick & Widdicombe, 1971) but does not usually alter lung elastic-recoil pressure (Nadel & Tierney, 1961) and certainly does not alter the rate of recovery of recoil pressure after a full inhalation (Marshall & Widdicombe, 1961). Thus any alteration in expiratory flow rates after histamine should simply reflect changes in bronchial smooth muscle tone. Indeed, in contrast to water, the breathing of histamine significantly reduced expiratory flow rates for all four types of expiratory manoeuvre. Furthermore after histamine both partial exhalations with 0 and 15 s breath holds and maximal exhalations with a 15 s delay at TLC had lower expiratory flow rates than the normal exhalation performed immediately on attaining TLC. This suggests that during the time delay airway tone was being restored towards a pre-inspiratory level and that the volume at which this delay occurred seems less important as the reductions in expiratory flow rates, caused by histamine, were comparable in percentage terms for both maximal exhalations from TLC and partials from 70% of VC provided that there was a time delay before exhalation.

Thus, it is the time delay between full inhalation and full exhalation which is more important in determining restoration of airway tone, rather than the volume at which breath is held. Maximal exhalation with a 15 s breath hold appeared as sensitive as the partial exhalation performed in this way, for detecting histamine-induced bronchoconstriction.

Of necessity, in testing the relative importance of the time delay and volume from which forced exhalations are begun, we chose a protocol for partials (Green & Mead, 1974) which ensured exactly comparable volume histories for both maximal and partial exhalations; both involved a full inhalation. It could be argued that we were not therefore giving full justice to the concept of partial expiratory flow-volume curves, which often involve an inspiration to a lung volume well below TLC (Bouhuys et al., 1969) and therefore avoid much of the bronchodilatation involved in full inhalation. Indeed, the time delay incurred by slow exhalation from TLC to 70% of VC in our partials, some 5–6 s, may not be sufficient to restore airway tone to a prefull inspiratory level as a full inhalation may cause bronchodilatation lasting 45 (Higenbottam & Clark, 1980) or 60 s (Nadel & Tierney, 1961). Yet, we found that, after histamine, the reduction in expiratory flow rates was only slightly greater in those partial exhalations where an additional 15 s delay had been adopted (Table 2); the longer delay provided little further restoration of airway tone. It should be observed that after histamine the VC fell significantly in the partial exhalation with a 15 s breath hold (Table 2), but only to a small degree. This may have resulted in higher estimates of flow rate for a given percentage of VC than estimates made before histamine. However, any error is likely to have been small as it is usually assumed that VC, if reduced by bronchoconstriction, does so because of an increase in residual volume with no change in TLC. Furthermore, performed in this way, partial expiratory flow-volume curves (Green & Mead, 1974) are relatively reproducible, both in terms of expiratory flow rate and VC (Table 1) and were easily performed by our untrained volunteers.

Forced spirometry should perhaps be performed after a standard breath hold at TLC. The expiratory flow rates so obtained may be as sensitive in detecting airways obstruction as the partial expiratory manoeuvres begun from below TLC and, although further work is needed to substantiate this, such delayed maximal exhalation is certainly more sensitive than spirometry performed immediately on attaining TLC. Indeed measurements such as FEV1.0 and peak expiratory flow rate show a greater reduction after histamine if breath is held for 15 s at TLC than if the maximal exhalation is made without any delay after the inspiration. As a corollary, variation in the delay between a full inhalation and subsequent forced exhalation may well account for some of the recognized intrasubject variation of the maximal expiratory flow-volume curve in healthy subjects.

References

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