Detection and interaction of elastic and flow-resistive respiratory loads in man

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Summary

1. The detection of added inspiratory airflow resistances was studied in normal individuals under two circumstances: first, while breathing unhindered, and secondly, while breathing against continuously applied ('basal') inspiratory elastic loads. The addition of basal elastic loads resulted in impaired detection of flow-resistive loads whether expressed as added flow resistance or as a proportion of the basal flow resistance.

2. When loads were plotted on a logarithmic scale, load-detection relationships were linear, permitting both threshold and slope of the detection response ('sensitivity') to be assessed. Impaired detection associated with basal elastic loads was shown to be due to a raised threshold without change in 'sensitivity'.

3. When the flow resistances submitted for detection were expressed as a proportion of the sum of the basal flow resistance and added elastance, the probability of detection was independent of the magnitude of the added elastance.

4. The interaction between basal elastic and added flow-resistive loads suggests that at the time of detection the basal elastance acts in a manner similar to that of an added flow resistance.

5. Added basal flow resistances had no significant effect on the detection of threshold elastic loads.

Key words: elastic loads, flow-resistive loads, respiratory load detection.

Introduction

The ability of normal men to detect added flow-resistive loads was studied by Bennett, Jayson, Rubenstein & Campbell [1] and Wiley & Zechman [2], using a number of different loads selected to give a probability of detection varying from 0 to 100%. Both groups expressed the threshold of detection as the load at which 50% detection occurred. Bennett et al. [1] noted that loads of the order of 25% of basal airway resistance were required to reach the threshold of detection in their normal subjects. Wiley & Zechman [2] studied the effect on detection of increasing basal airway resistance and showed that, whereas detection was impaired when added resistance was expressed in absolute units, when expressed as the ratio of added to basal flow resistance the threshold was not altered. Furthermore, they pointed out that this finding was similar to the behaviour of other sensations, e.g. detection of changes in weight when expressed in an analogous way (Weber law). Fechner [3], in studying the detection of added weight to the outstretched hand to which basal weights of different magnitude had already been added, noted that the ratio of added to basal weight at the threshold of detection only approached a constant value when the basal weights were large: he attributed this apparent discrepancy at smaller basal weights to the omission of the weight of the arm from the denominator. It is therefore surprising that, in the respiratory system, detection of the ratio of added to basal flow resistance should be constant at different levels of basal resistance because inspiratory muscles operate not only against flow resistance but the considerable elastances of the lungs and thorax (which might
be considered analogous to the weight of the arm). These considerations led us to investigate the effect of additional basal elastic loads on the ability to detect added flow resistances, and vice versa.

Methods

Subjects

Five adult volunteer subjects (four males and one female) aged 24–53 years were studied. All subjects had normal spirometry and normal airway resistance as measured in a body plethysmograph. None of the subjects was familiar with psychophysical measurement.

Apparatus (Fig. 1)

Elastic loads consisting of empty oil drums ranging from 240 to 780 litres capacity were connected to the breathing circuit through a ‘bag-in-bottle’ system to minimize the risk of cross-infection. Resistive loads consisted of Perspex tubes shaped to have pressure–flow characteristics similar to those of normal airways. They were arranged on the periphery of a cylinder which could be rotated to introduce individual resistances as required into the inspiratory limb of the circuit. A low resistance (0.08 cm water l–1 s at 0.5 litre/s) gravity-operated two-way valve permitted the separation of the two phases of respiration. The dead space of the valve and mouth piece was approximately 70 ml. Two expiratory valves, one in the elastic loads circuit and the other in the expiratory limb of the breathing circuit, were used to prevent pressure build-up in the system. Carbon dioxide was absorbed by a cannister of soda lime in the expiratory limb. During preliminary experiments end-tidal $\text{PCO}_2$ was measured with a carbon dioxide analyser (URAS) and was shown not to change significantly during each experimental run. Oxygen was added to the circuit at a constant rate (1.5 litres/min) to prevent hypoxia and to ensure that there was always an adequate volume in the bag at the beginning of each breath; the excess escaped through the expiratory valves.

Mouth pressure was monitored continuously with a pressure transducer (Elema Scholander EMT 32 no. 515) and its output recorded on a multichannel recorder (Mingograph 81).

The whole apparatus and operator were screened from the subject and care was taken to eliminate extraneous sources of information about addition of loads. The subject indicated detection of load by pressing a buzzer which also signalled on the recorder. For detection of flow resistance during basal elastic loading, the tap upstream from the resistance drum was closed so that the subject breathed against the selected elastic load. Between the addition of flow-resistive loads the resistance drum was bypassed.

For detection of elastic loads during basal resistive loading, selected flow resistances remained in the breathing circuit throughout while different elastic loads were introduced for one breath for detection.

Procedures

Four experiments were performed on each subject. In the first the detection of flow-resistive loads without added elastance was measured. In the following three, detection of flow-resistive loads was repeated while the subject was breathing against a background of inspiratory elastic loads of 0.15, 0.25 and 0.5 kPA/l (1.5, 2.5 and 5.0 cm water/l), exhibited in random order.

The subject, wearing a nose-clip and seated in a

![Fig. 1. Apparatus for load detection. The circuit for elastic loads, represented by four circles, is separated from the airway resistance circuit by a ‘bag-in-bottle’ to minimize risk of cross-infection. Different flow resistances can be introduced at ‘variable resistance’. The subject breathes via the mouthpiece at the extreme right and is screened from the remainder of the apparatus to avoid visual clues.](image-url)
chair, breathed quietly through the mouthpiece. A remote signal button was held in the dominant hand and pressed if a load was detected. Subjects were not blindfolded but they invariably elected to close their eyes for better concentration. They were given a preliminary trial with different loads to familiarize them with the 'resistive' sensation.

The manner of presentation of loads was different from that of Bennett et al. [1] and Wiley & Zechman [2] in that a single loaded breath was used. Flow-resistive loads were introduced into the circuit during expiration so that they became applied during the next inspiration; they were removed during the following expiration whether the subject signalled detection or not. Each load was presented on ten occasions, the sequence being randomly ordered. Each correct detection was assigned one point; any experiment in which detection was signalled on more than two occasions when no additional load had been applied was excluded. Probability of detection at each level of resistive load was calculated as the number of correct detections divided by ten, the number of presentations of the load.

During the experiments without added elastic loading, six levels of resistance ranging from 0.025 to 0.125 kPa l⁻¹ s⁻¹ (0.25-1.25 cm water l⁻¹ s⁻¹) were used. With elastic loading a higher range of resistance up to 0.45 kPa l⁻¹ s⁻¹ (4.5 cm water l⁻¹ s⁻¹) was required to achieve 100% detection.

Similar procedures were adopted in a second series of measurements in four subjects in which detection of added elastic loads was measured, both without basal loading and at four different basal levels of inspiratory flow resistance. For each level of flow resistance different elastic resistances were introduced randomly on ten occasions, the same system for indicating detection being used.

Results

Fig. 2 shows the effect of three levels of added elastic loads on the detection of added inspiratory flow resistance in one subject. The probability of detection (P) of added flow resistance was progressively reduced by the added elastic loads. Even the addition of an elastic load of 0.15 kPa l⁻¹ s⁻¹ (1.5 cm water l⁻¹ s⁻¹), which was subthreshold for the individual, produced a significant shift in the detection curve.

Figs. 3 and 4 show the mean detection curves obtained from the pooled data of the five individuals, when the loads were expressed as added flow resistance and the ratio of added to basal flow resistance (the latter being the airway resistance of the subject plus that of the ap-
Effect of three levels of added elastic loads on the mean detection of added inspiratory flow resistance in five subjects; error bars indicate ± 1 SD. Abscissa shows log flow-resistive loads expressed as a fraction of the basal flow resistance (R): O, unloaded; □, 0.15; △, 0.25; ▽, 0.50.

Fig. 5. Effect of three levels of added elastic loads on the mean detection of added inspiratory flow resistance in five subjects; error bars indicate ± 1 SD. Abscissa shows log flow-resistive loads expressed as a fraction of the basal flow resistance (R): O, unloaded; □, 0.15; △, 0.25; ▽, 0.50.

Effect of three levels of added elastic loads on mean detection of added inspiratory flow resistance in five subjects; error bars indicate ± 1 SD. Abscissa shows log flow-resistive loads expressed as a fraction of the basal flow resistance (R): O, unloaded; □, 0.15; △, 0.25; ▽, 0.50.

Fig. 6. Effect of three levels of added elastic loads on the mean detection of added inspiratory flow resistance in five subjects; error bars indicate ± 1 SD. Abscissa shows log added flow-resistive load as a fraction of the sum of the added elastic load (Eₘ) and basal flow resistance (R): O, unloaded; □, 0.15; △, 0.25; ▽, 0.50.

The vertical bars on Figs. 3–6 indicate means ± 1 SD, a normal distribution of results being assumed.

In Fig. 5 the data shown in Fig. 4 have been plotted with the logarithm of the ratio of added to basal flow resistance on the abscissa. The detection of resistive loads is seen to vary linearly with the logarithm of the load. When expressed in this way, the slopes of the detection curves were unchanged, the effect of the added elastances being to change only the intercept (threshold).

Fig. 6 was obtained when detection was expressed as the logarithm of the ratio of added to basal flow resistance plus the added elastance. No significant difference in the detection of elastic loads was observed with different levels of basal inspiratory flow resistance (Fig. 7).

Discussion

When load-detection data are plotted with linear scales a curvilinear relationship is obtained. The threshold of detection has usually been arbitrarily taken as the load necessary to achieve 50% detection, which has the disadvantage of ignoring data at other levels of detection. The shape of the curve suggested an exponential relationship between load and detection and this was supported by the linear relationship obtained when detection was plotted against the logarithm of the added load. Plotted in this way load-detection data can be expressed not only in terms of threshold (at any level of detection) but also as their slope (which we refer to as the ‘sensitivity’ of the mechanism of detection because it indicates the degree of increase in detection for each increment in stimulus).
Respiratory load detection and interaction

With this semilogarithmic presentation the effect of added elastic loading was seen to increase only the threshold of flow-resistive detection and not to alter 'sensitivity' as defined. To try and identify the stimulus to the receptors under these circumstances we plotted detection against a number of different possible expressions of the total load, for example change of impedance expressed as a proportion of total impedance, but this did not result in superimposition of load-detection lines. The only combination that achieved this was the ratio of added flow resistance to the basal flow resistances plus the added elastance. This finding suggests that the subjects' basal pulmonary and thoracic elastance did not influence the detection mechanism for resistive loads because addition of the thoracic elastance to the denominator would no longer permit prediction of probability of detection.

For resistive loads, probability of load detection is related to the ratio of added flow resistance to basal flow resistance [2]. The finding that, for combination of resistive and elastic loads, resistive-load detection is related to the ratio of added flow resistance to the basal flow resistance plus the added elastance suggests that the added elastance is acting under these circumstances in a way similar to a flow resistance.

The nature and location of receptors for load detection remains uncertain. The suggestion that they may reside in the upper airways [4] is in our opinion untenable because the effect on the detection of an added flow resistance is similar whether an increased basal airflow resistance is applied externally, as in experiments on normal subjects, or exists internally below the upper airway, i.e. in patients with increased resistance to airflow in the bronchi ([2]; S. U. Shahid & J. B. L. Howell, unpublished work).

The reduced detection of added flow resistances by elastic loading in our studies is in striking contrast with the lack of effect of restricting the expansion of the thorax by chest clamping [5] or by chest strapping (S. U. Shahid, unpublished work).

External loading via the airway affects the whole of the musculoskeletal apparatus involved in inspiration, whereas clamping or strapping of the thoracic cage restricts mainly the rib cage, allowing, for example, the diaphragm to continue to operate with minimal interference. These findings suggest that, under these circumstances, receptors in the diaphragm may be sufficient to detect added loads. However, it has been suggested that because load detection was unimpaired in a subject with diaphragmatic paralysis, the diaphragm is not involved [4].

The effects of basal elastic loadings on the detection of inspiratory flow resistance contrast with the failure of basal inspiratory flow resistances to influence detection of added loads. In studies on the timing of detection of added loads Zechman et al. [6] have suggested that, because elastic loads at levels close to threshold are detected towards the end of inspiration when inspiratory flow rates are much reduced, flow resistances would not be expected to influence the detection of the elastic loads. Conversely, elastic loads would be expected to influence the detection of near-threshold flow resistances which tends to occur at times of maximal airflow.

It seems likely that closer analysis of the events occurring in the early part of inspiration during such combined loading may provide the clue to the nature of the stimulus and the likely receptor(s) involved in load detection.

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References