21 TOLERANCE TO EXTERNAL BREATHING RESISTANCE WITH PARTICULAR REFERENCE TO HIGH INSPIRATORY RESISTANCE

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INTRODUCTION

Many previous investigations have been made into the effects of external respiratory workloads in men to define acceptable standards for men wearing respiratory apparatus. A comprehensive study of the problem was made by Silverman et al. (refs. 1, 2) who investigated the effects on young men of breathing against resistance while working at various rates on a bicycle ergometer.

Cooper (ref. 3) and Senneck (ref. 4) reviewed the work of Silverman *et al.* and from it derived standards for the maximum permitted total rate of respiratory work done on a breathing apparatus. Cooper stressed that Silverman's subjects were not accustomed to breathing through resistances and only exercised for 15 min, whereas most of the men likely to wear respiratory apparatus would be trained in their use and would probably be required to wear them for a much longer period.

Underground workers in the British coal industry have recently been issued emergency "self-rescuer" filter-type apparatus to protect them from carbon monoxide. These respirators are designed to last for about an hour and should enable men to reach safety following an underground fire or explosion. The potential use of the equipment by a large population of men has prompted us to re-examine the ability of men to exercise while breathing through graded inspiratory resistances. The information obtained should be relevant to the design and use of most types of breathing equipment. We were not concerned with the effects of the added resistances on such factors as the rate or depth of breathing or on gas exchange but simply on the subjects' ability to tolerate the added respiratory workload.

Particular care was taken to ensure that the apparatus and exercise were appropriate to that encountered in practice. In most industrial breathing equipment the relation between airflow and work rate is far from linear over an extended range of airflows, so experimental resistances were constructed having similar nonlinear characteristics. The duration and severity of exercise were intended to match and exceed those anticipated in men escaping in an emergency, and be similar to those encountered in routine use. The exhalation valve was of a standard low resistance type and extra resistances were added only to the inhalation side.

METHODS

The relationship between the pressure p required to maintain a rate of airflow dV/dt through a respiratory apparatus may be expressed to a close approximation, as $p = k \, (dV/dt)^n$ where n and k are constants characteristic of the resistance to flow of the apparatus. Single values of n and k may hold throughout a wide range of flow rates in some types of respiratory apparatus, while two or even three values may be required to define the pressure-flow relationship of the patterns of flow in other apparatus.

Several designs of experimental resistance were examined, but the design found to give the most appropriate values for n and k was constructed as follows. Several stainless steel plates (3.8 by 1.9 by 0.01 cm) that had a radius of curvature about their major axis of approximately 8 cm, were mounted in pairs, with their concave surfaces facing each other, into a perspex holder (fig. 21.1). Increasing the number of plates inserted into a holder increased the resistance to flow and vice-versa. This method of construction yielded the desired resistance to airflow. The resistances were calibrated during their construction, and when a particular resistance was judged to have an acceptable value, the plates were fixed in position by epoxy resin along their edges. Ten such resistances were produced (fig. 21.2).

The experimental mouthpiece assembly (fig. 21.3) consisted of the head and headstrap of a self-rescuer into which had been inserted a pressure measuring port. The experimental resistance and respirometer were connected by a short piece of rubber tubing to the mouthpiece. The complete apparatus weighed about 415 g and was easily dismantled for cleaning and sterilizing.
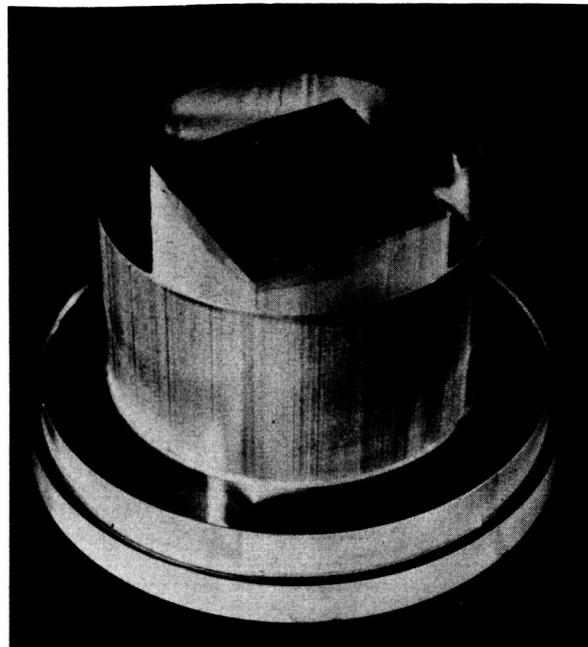
Figure 21.1 *Experimental inspiratory resistance.*
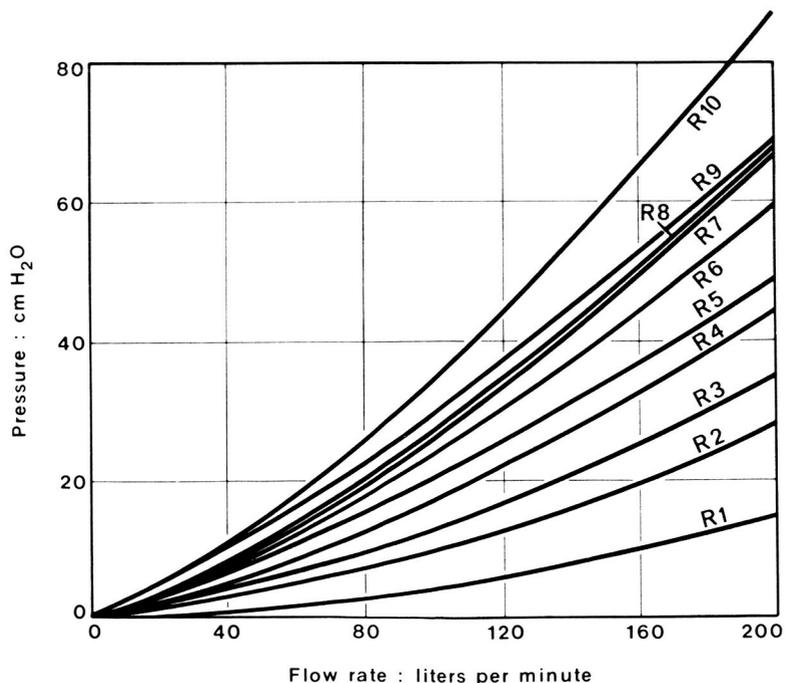
Figure 21.2 *Pressure-flow curves of resistances R_1 to R_{10}.*

The ventilation of each subject was measured with a respirometer (ref. 5), a small instrument that allows the subject to exercise freely. Each respirometer was calibrated by means of a breathing simulator.

The experimental subjects were all members of the Mines Rescue Service of the British National Coal Board. Seven were full-time members and the remainder were part-time men who were also employed in various underground trades. Their ages ranged from 21 to 45 years. A total of 158 men participated in the study; each man took part in only one experiment.

The exercise consisted of a 30-min walk on a treadmill whose speed and inclination could be varied. The work rate was altered between subjects so that a wide range of minute ventilations was obtained. Each man wore shorts, boots, and stockings as well as a safety helmet, battery, and cap lamp similar to those used when working underground. He was given a brief description of the experiment and of its aim, and was then allowed to take a short practice walk on the treadmill. The ten resistances were allocated at random among the subjects, who wore them throughout the exercise.

Figure 21.3 *Experimental mouthpiece assembly.*

Each man was questioned after completing the exercise. He was asked to select from a printed card the condition that most closely described the effect of the apparatus on his breathing. The wording of the questionnaire was based on phrases used by the men in conversation. The choices are shown in table 21.1. Several subjects expressed a need for intermediate answers, and these were recorded as one/two or two/three, etc.

Table 21.1 *Questionnaire shown to each subject after completing the exercise.*

Did you find breathing :-

1. Not noticeable

2. Noticeable but not difficult

3. Difficult

4. Very difficult

CALCULATION OF THE EXTERNAL WORK OF BREATHING

Inspiratory Work Rate

The resistances were designed to have characteristics similar to those of breathing equipment in current use. However, the nonlinear pressure-flow relationships necessitate some complexity in the calculation of the respiratory work rate. The mathematical approach used allowed the work rate to be calculated from the minute volume, peak pressure measurement, and the proportion of each respiratory cycle spent on inhaling or exhaling. The range of flow rates encountered in the experiments permitted single values of n and k for each resistance to be used for all the calculations.

It can be shown that when the flow pattern is sinusoidal and the pressure-flow curve of the external resistance can be represented by one value for n and k, then the inspiratory work done per minute (W_i) is given by

$$W_i = \frac{k}{100} \frac{\dot{V}_E^{n+1}}{I^n} \left(\frac{\pi}{2}\right)^n \int_0^{\pi/2} \sin^{n+1} x \, dx \qquad \text{kg-m/min} \tag{1}$$

where $\dot{V}_E$ is the minute volume and I is defined by

$$I = \frac{\text{time occupied by one inhalation}}{\text{time occupied by one complete respiratory cycle}}$$

In practice, the value of n is not an integer; therefore, the integral in equation (1) is not easily solved. A graphical solution was obtained for noninteger values of n, after solving equation (1) using values of $n = 1, 2, 3$.

It can also be shown that when the flow pattern is rectangular or triangular the inspiratory work done per minute is given by

$$W_i = \frac{k}{100} \frac{\dot{V}_E^{n+1}}{I^n} \text{ kg-m/min} \tag{2}$$

for rectangular flow and

$$W_i = \frac{k}{100} \frac{\dot{V}_E^{n+1}}{I^n} \frac{2^{n+1}}{n+2} \text{ kg-m/min} \tag{3}$$

for triangular flow. It follows, therefore, that for each resistance used in the experiments the equations for external inspiratory work rate, albeit a sine, rectangular or triangular waveform, simplify to

$$W_i = A \frac{\dot{V}_E^{n+1}}{I^n} \text{ kg-m/min} \tag{4}$$

where A is a constant for a particular resistance and waveform.

By introducing the concept of a shape factor (Q), it is possible to quantify the shape of the waveform and thereby take account of its shape when calculating external respiratory work. This shape factor is defined as the ratio peak flow rate/minute volume; that is, the larger the peak flow rate (for a particular minute volume) the larger the shape factor. It can be shown that
1. The peak flow rate in sinusoidal flow = $\pi \times$ minute volume.
2. The peak flow rate in rectangular flow = $2.0 \times$ minute volume.
3. The peak flow rate in triangular flow = $4.0 \times$ minute volume.
From calculated values of the constant A, for sinusoidal ($Q = 3.14$), rectangular ($Q = 2.0$) and triangular ($Q = 4.0$) flow, graphs of shape factor against A were drawn for each resistance.

The shape factor Q was determined for each experiment and the value of the constant A deduced from the appropriate graph. The ratio I was also determined for each experiment from the continuous recording of the pressure in the mouthpiece. The external inspiratory work rate was then calculated from equation (4).

Validity of the Calculation

Calculation results were compared with those obtained by a conventional method. The inspiratory work rate in ten subjects was calculated from the continuous record of the pressure drop across the resistances. Each measurement of pressure was associated with its appropriate work rate as derived from a knowledge of the pressure-flow relationship of the resistance in use. The total expenditure of work during each inspiration was then obtained by integration of the area under the curve. Ten respiratory cycles were examined in each subject, and the work rates obtained were compared with

those obtained by indirect calculation using equations (1) through (4). The correlation coefficient between the two methods was 0.99.

Expiratory Work Rate

Although the method of determining the external expiratory work rate was identical to that used for the inspiratory work rate, the calculations were more difficult because the pressure-flow characteristics of the expiratory valve could not be defined by single values of n and k. It was therefore necessary to evaluate the general equations for respiratory work rate; the results of these calculations were obtained by means of a FORTRAN program on an ICL 1907 computer. The external expiratory work rate for each exercise was then obtained by interpolating, using the appropriate shape factor, between the work rate calculated for sinusoidal, rectangular, or triangular waveforms.

RESULTS

The replies to the questionnaire were divided into two groups. Those men who indicated that their breathing was not difficult (response 2 or less) were deemed to have an acceptable respiratory workload. Those who assessed their sensation of breathing as more difficult than "noticeable but not difficult" were considered to have an excessive respiratory load. The relation between the responses and the rate of respiratory work is illustrated in figure 21.4 with the associated minute ventilation. The curves shown in figure 21.4 will be referred to later in the text.
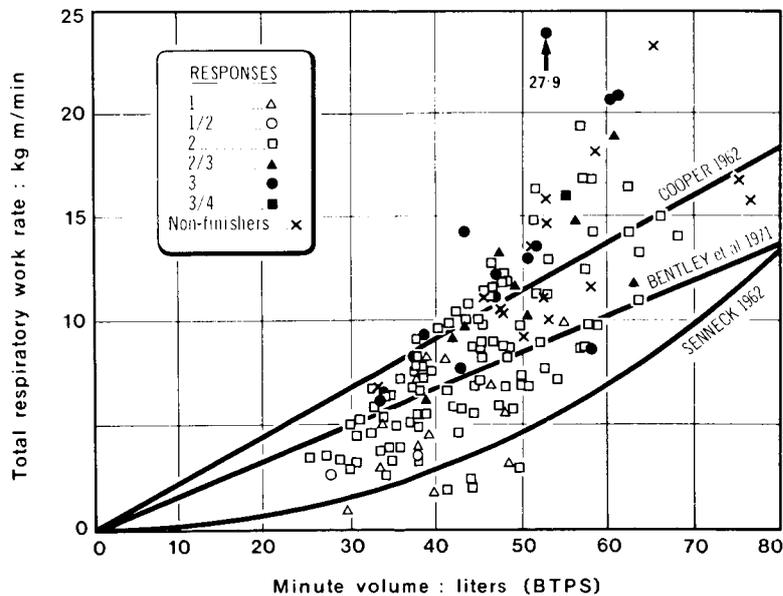
Figure 21.4 *Subjective response to breathing resistance related to total respiratory work rate and minute volume.*
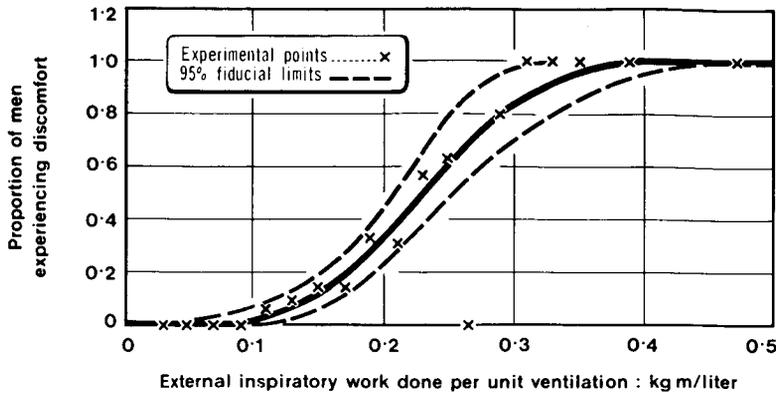
Figure 21.5 *Proportion of men experiencing discomfort related to inspiratory work rate.*

The distribution of the points in the figures is determined by the design of the experiment. Since a fixed number of resistances was used by men exercising at various rates on the treadmill, the overall pattern of the points reflects the pressure-flow characteristics of these particular resistances. There is thus no general physiological relationship implied by the correlation between minute ventilation and respiratory work rate apparent in figure 21.4.

However, the figures do give information about the factors determining the sensation of discomfort when breathing through an inspiratory resistance. Although there is a good deal of overlap between the two groups it can be seen that both the rate of respiratory work and the minute ventilation play a part. A workload apparently judged acceptable at a high minute ventilation may be unpleasant at a lower minute ventilation. The relationship may be simplified by calculating the inspiratory work done per liter of air breathed. The subjective responses to this single parameter are shown in figure 21.5. The data are seen to fit closely to a sigmoid dose-response type of curve that expressed the probability that a given value on the abscissa will be judged unacceptable by the population of men tested. The fitted curve and 95 percent fiducial limits were obtained by the method of probit analysis (ref. 6). Similar data for the total respiratory work did not give such a close fit to a single line (fig. 21.6). This is not unexpected since the men, when commenting on their assessment of the apparatus, tended to concentrate on the characteristics of the inspiratory resistance.

Figure 21.6 *Proportion of men experiencing discomfort related to total respiratory work rate.*

The relation between the subjective response and the measurements of the peak inspiratory pressure swing was also examined. Again there is a good deal of overlap between the two groups of points but no suggestion of association with minute ventilation. The level of the peak pressure swing alone appears to distinguish those men who felt discomfort on breathing from those who did not. The results are expressed in probability form in figure 21.7.

A highly significant correlation ($P < 0.001$) was found by Students t test between the proportion of subjects noting discomfort on breathing and each of the parameters shown in figures 21.5, 21.6, and 21.7.

It was found that, in practice, the waveform was neither rectangular nor truly sinusoidal, but rather a flattened sine wave. The degree of flattening did not depend on the magnitude of the resistance. Similarly, the proportion of each respiratory cycle spent on inspiration varied little throughout the entire range of the experiments. The shape factor was also nearly constant ($Q = 2.67 \pm 0.23$). These studies thus gave no evidence that the pattern of breathing changed significantly in response to varying inspiratory workloads within the range tested.
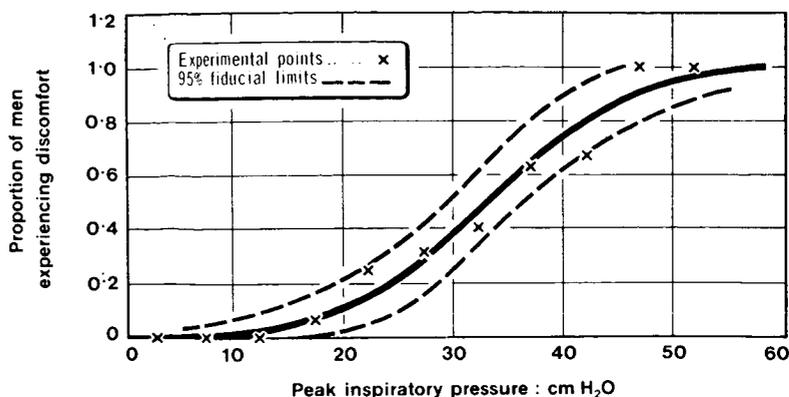
Figure 21.7 *Proportion of men experiencing discomfort related to peak inspiratory pressure.*

The results were examined to see whether men who found the inspiratory workload acceptable (group 1; response 2 or less) had a higher ventilatory capacity than those who were distressed (group 2; response two/three or greater) when breathing under the same conditions (table 21.2). Eighteen subjects were selected from each group, so that each man in group 1 was matched with a man in group 2 based on the following criteria: treadmill speed and inclination, resistance to breathing, and body weight and height. It can be seen that there was a slight but insignificant difference in the ventilatory capacities of the two groups, although the average age was slightly higher for group 2. However, group 2 had, on average, a significantly higher peak inspiratory pressure, and inspiratory and total respiratory work done per minute and per liter of air breathed (table 21.2).

Table 21.2 *Ventilatory characteristics (mean + S.D.) of 18 subjects (Group 1) who found the work of breathing acceptable compared with 18 subjects (Group 2) who found the work of breathing difficult.*

Group	Response†	Age yr	Weight kg	Height cm	FEV₁‡ liters	FVC‡ (BTPS)	Pp cm H_2O	V_E liters min^{-1} BTPS	f min^{-1}	W_i kg m min^{-1}	W_t kg m min^{-1}	W_i/V_E kg m $liter^{-1}$	W_t/V_E kg m $liter^{-1}$
1	< 2	31·5 ±5	73·7 ±7·5	172·7 ±7·8	3·56 ±0·66	4·45 ±0·74	31·8 ±6·3	46·2 ±10·7	24·4 ±4·5	9·6 ±2·8	10·8 ±3·9	0·208 ±0·040	0·228 ±0·047
2	> 2/3	34·1 ±7	73·7 ±7·5	173·0 ±6·1	3·85 ±0·61	4·84 ±0·56	35·7 ±7·7	49·2 ±10·9	24·5 ±5·8	13·9 ±5·5	15·1 ±7·4	0·282 ±0·068	0·312 ±0·084
Differences (P values*)		-	-	N.S.	N.S.	< 0·05		N.S.	N.S.	< 0·01	< 0·01	< 0·01	< 0·001

Pp = Peak inspiratory pressure; W_i, W_t = Inspiratory and total respiratory work done per minute;
V_E = minute volume; f = breathing frequency; W_i/V_E, W_t/V_E = inspiratory and total respiratory work done per liter.
   †See Table 21.1   ‡For 10 subjects only in each group;   *single sample t test: significance levels

DISCUSSION

The sensation of discomfort during breathing in these experiments was related closely to the additional work done per liter of air inhaled and to the peak pressure swing. However, the former was calculated by dividing the inspiratory work rate (kg-m/min) by the minute ventilation (liters/min). As noted by Cooper (ref. 7) the derived term has the dimensions of pressure. The results therefore indicate that the degree of dysponoea (shortness of breath) was a function of the negative intrathoracic pressure. These conclusions support those of Silverman (ref. 2) and Cooper (ref. 3) but not the findings of McIlroy (ref. 8) who considered that the absolute respiratory workload was a major factor in the causation of dyspnoea.

The levels of resistance investigated by us and also by Silverman (ref. 2) fall between those that are detectable but not uncomfortable (refs. 9, 10) and those that are the maximum tolerable (refs. 11, 12, 13). The dividing line in our experiments (fig. 21.4) is drawn at the point where subjective discomfort is first noticed.

Two factors must be considered in using the results to formulate standards that may be used for acceptance testing of respiratory apparatus. In the first place, the standard must not be set so low that it is ignored. It also is necessary to ensure that the most men can and will use the apparatus. A compromise is suggested by taking a value from figure 21.5 such that 90 percent of the population tested will not experience respiratory discomfort. The appropriate level is 0.14 kg-m/liter (1.4J/liter) of air inhaled.

This unit has the dimensions of pressure and it can be shown that 0.14 kg-m/liter is equivalent to a pressure drop across the inspiratory valve of 14 cm H_2O (1.4 kN/m^2) during conditions of steady flow. By applying the criteria used to obtain a limit on inspiratory work rate it can be deduced from figure 21.6 that the total external respiratory work permissible when using low resistance expiratory valves amounts to 0.17 kg-m/liter (1.7J/liter) of air breathed.

These levels are below those suggested by Cooper (ref. 3) but above those suggested by Silverman (ref. 2) and Senneck (ref. 4) (fig. 21.4). Their results refer to the situation in which there is a combination of inspiratory and expiratory resistances.

The type of airflow used in the laboratory testing procedure must be considered in defining an acceptable resistance for the assessment of respiratory apparatus. We have found that the normal waveform of subjects breathing through inspiratory resistances is flattened with a mean shape factor (peak inspiratory flow/minute volume) of 2.7. We have also shown that some discomfort in breathing was experienced by 10 percent of the population of the peak inspiratory pressure exceeded 19.5 cm H_2O (1.95 kN/m^2) (fig. 21.7). If apparatus is tested with a sine wave pump, the peak inspiratory flow approximates to $\pi\times$ minute volume. Under these conditions, therefore, it is suggested that the peak pressure drop across the equipment under test should not exceed $\pi/2.7 \times 19.5 = 22.3$ cm H_2O (2.2 kN/m^2). When using the steady flow method the rate of airflow must be 2.7 times the minute volume.

With either method of testing, the airflow must be appropriate to the upper limit of minute ventilation likely to be encountered in the men wearing the apparatus.

6-6

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