

The Determination of the Breathing Waveform
of Mines Rescue Personnel Wearing Simulated
Closed Circuit Breathing Apparatus

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ABSTRACT

The flow breathing patterns of Mines Rescue personnel have been measured using breathing resistances to simulate those of a modern closed circuit breathing apparatus. Three workrates were undertaken, producing average minute volumes of 34, 55 and 68 litres/min Body Temperature and Pressure, Saturated (BTPS). An analysis method has been developed to investigate breathing waveform patterns, and a set of average waveforms has been produced for each exercise. The shapes of the waveforms have been studied, and factors to describe the shapes have been produced. The characteristic shapes of the breaths change between exercises and within the exercises. The peak flow of the inspiration phase occurs at a constant interval, about 0.6 seconds, from the beginning of the phase; the peak of the exhalation phase occurs after a constant proportion, approximately 50%, of the phase. The overall shapes of the waveforms are flatter than sinusoidal waveforms and have a sharpness factor Q of between 2.6 and 2.7 irrespective of workrate. (For comparison, $Q = 3.141$ for a sinusoidal waveform, $Q = 4$ for a triangular waveform, and $Q = 2$ for a rectangular waveform).

INTRODUCTION

BREATHING APPARATUS WORN BY MEN

When men breath against resistance, it has been observed that they tend to modify their breathing waveforms. The form of the change depends on several factors, including the level of resistance, the presence of carbon dioxide, and the work rate. A Closed Circuit Breathing Apparatus (CCBA) provides all these factors; the apparatus imposes a breathing resistance to both exhalation and inhalation, the mouthpiece dead space and inefficiencies in or exhaustion of the purifier cause carbon dioxide inhalation, and the wearer is expected to do work whilst wearing the CCBA.

The factors are interrelated in that the condition of the air which the wearer inspires from the CCBA is affected by the workrate. In a CCBA, the purifier scrubs carbon dioxide from exhaled breath in an exothermic reaction, therefore the highest inspired temperatures and carbon dioxide concentrations may be expected to occur after the highest flow rates through the apparatus.

BREATHING APPARATUS ON BREATHING SIMULATORS

In the UK, CCBA are currently tested for performance using breathing simulators which operate with a sinusoidal flow breathing waveform, at 40 litres/min BTPS, with 5% exhalation concentration of carbon dioxide.

According to the performance of certain CCBA on the breathing simulator, the user of the apparatus would have to inspire air at a temperature which would be considered unbearable; however these apparatus have been used without difficulty all over the world.

There would then seem to be justification for testing CCBA on breathing simulators which do not utilise a sinusoidal waveform, but instead one which more accurately represents the waveform produced by men. Breathing simulators which can vary the breathing waveform have been developed (Nelson et al., 1972; Reimers, 1984), and one has been developed at RLSD which will form the basis of a future report.

The waveforms typical of men wearing CCBA must be identified before these variable waveform machines can be used to test CCBA.

PREVIOUS WORK ON FLOW WAVEFORMS

Previous work on the measurement of breathing flow waveforms is scanty. Silverman (1951) reviewed previous work and found little information. In his own work, he tested subjects breathing air at different work-rates using apparatus with an inspiratory resistance of 640 Pa (64 mm H₂Og) and an expiratory resistance of 410 Pa (41 mm H₂Og) when measured at 85 litres/min constant flow. His results have since become a much used source of waveforms for variable waveform breathing simulators.

Zechman et al (1957) tested eleven subjects breathing air at a low work rate of 27 W (166 kgm/min) with inspiratory resistances or expiratory resistances or both, and produced waveforms for each condition. He showed that the tidal volume (V_T) stayed largely constant when inspiratory resistances alone were added, but V_T increased with expiratory resistance. He also showed that the time for the inspiration phase (T_I) increased but the time for the exhalation phase (T_E) remained constant when breathing against inspiratory resistances only, and showed a corresponding effect with expiratory resistances only. The time of each phase was greater with resistances in both phases. This effect had also been observed by Silverman at work-rates of less than 180 W(1107 kgm/min).

Bentley and Love (1973) produced descriptive shape factors for waveforms when testing men breathing against inspiratory resistances only, but comprehensive waveforms were not produced. Raven (1979) in a review of physiological changes arising from the wearing of respirators called for more work on shape factors, especially at higher work rates.

There has been much work carried out on the interrelationships of V_T with T_I and T_E under resistance and carbon dioxide rebreathing. Clark and von Euler (1972) and Gardner (1977) showed a two stage behaviour. At rest and low workrates, T_I remained constant with increasing V_T but T_E shortened significantly. As V_T increased above half vital capacity, T_I started to shorten, and T_I and T_E

became nearly equal. The relationships between V_T and T_I and V_T and T_E above this breakpoint were curvilinear and consistent for each subject but very different from subject to subject. Newsome, Davis and Stagg (1975) found that the minute volume ($\dot{V}$), being the product of V_T and the breathing frequency $1/T_{TOT}$ where $T_{TOT} = T_I + T_E$, was constant from breath to breath in resting subjects i.e. that V_T and T_{TOT} were linearly correlated and crossed the V_T and T_{TOT} axes near the origin.

It has been observed that minute volume is reduced when oxygen is breathed instead of air, but the effect on the waveform has not been investigated.

OBJECTIVES

The object of this research is to measure the breathing patterns of typical users of CCBA, and pick a characteristic flow pattern, which is a representation of a typical breath to which the CCBA would be subjected. In addition, the descriptive parameters of breath shapes are to be investigated.

In this first trial of a planned series, the work of Silverman is to be repeated to establish the waveform of men breathing air when breathing against resistances typical of CCBA. The effect of oxygen, elevated temperatures and humidity, and carbon dioxide inhalation (apart from the mouthpiece dead space) are to be ignored. Essentially, this is to be a control experiment for later tests.

MEASUREMENT OF WAVEFORMS OF SIMULATED CLOSED CIRCUIT BREATHING APPARATUS

THE MONITORING EQUIPMENT

A mouthpiece assembly consisting of valves and monitoring equipment was constructed so as to approximate the resistance to flow characteristics of a modern CCBA, as shown in Figs 1 and 2. Also shown in Fig 1 are the resistances as used by Silverman. In the years since his work was carried out, the performance of CCBA has been improved. The resistance characteristic of an older type of CCBA has been improved. The resistance characteristic of an older type of CCBA is shown for comparison in Fig 1.

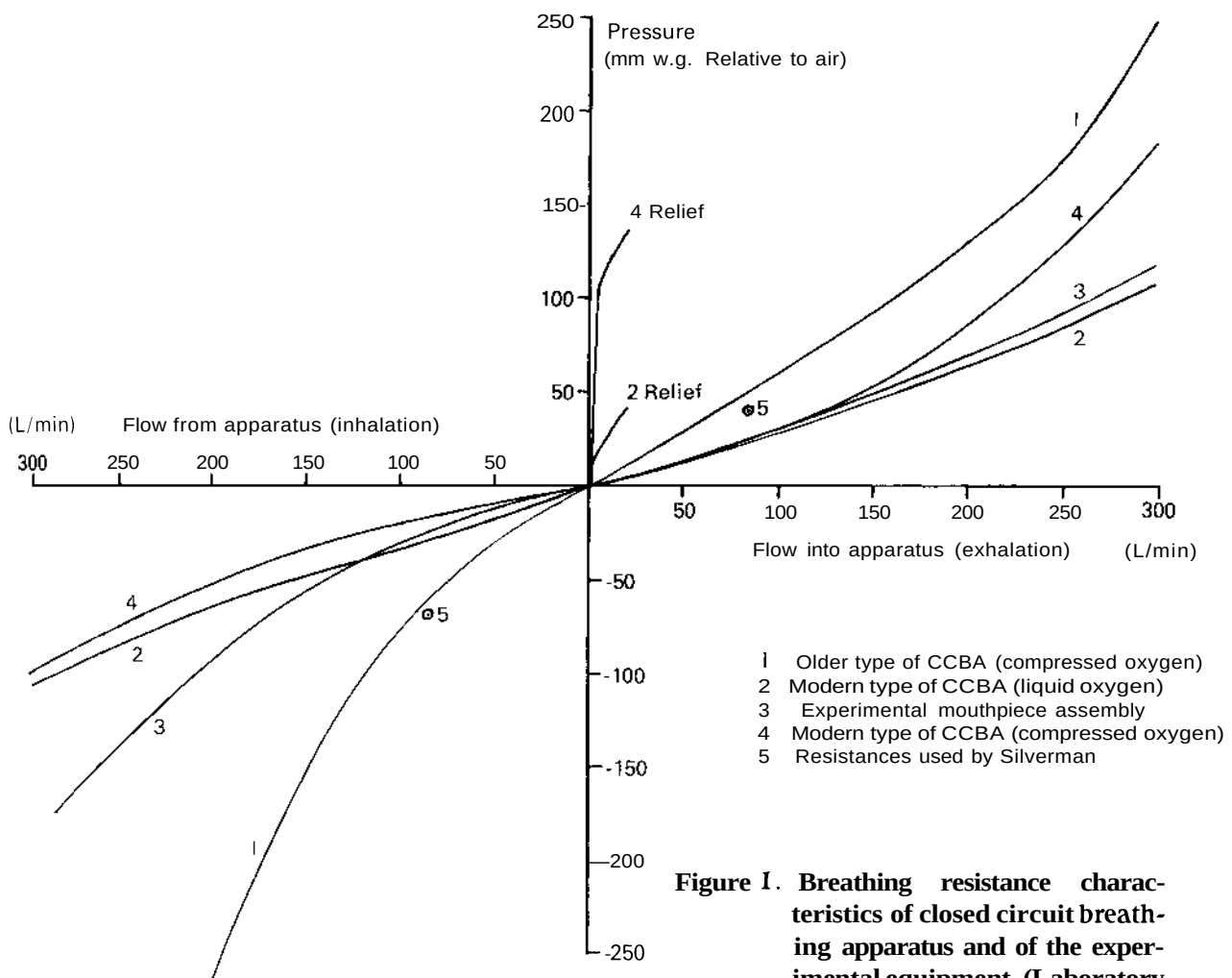


Figure 1. Breathing resistance characteristics of closed circuit breathing apparatus and of the experimental equipment. (Laboratory air at 20°C.)

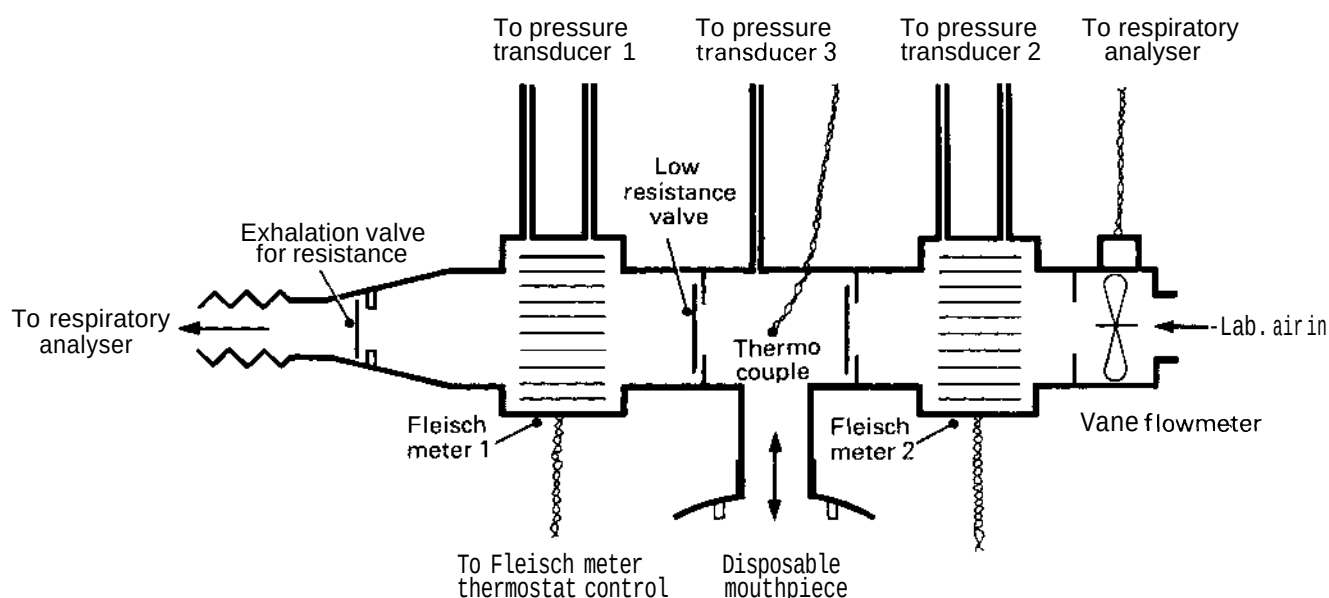


Figure 2. The simulated CCBA mouthpiece assembly.

Two types of monitoring systems were used. Minute by minute averages of uptake of oxygen, production of carbon dioxide, minute volume, tidal volume, breathing frequency and heart-rate were printed out by a respiratory monitoring system (P K Morgan). This utilised a vane respirometer on the inhalation side of the mouthpiece assembly, and a mixing box and gas analysis system to monitor the average condition of the collected exhaled air. Readings were analysed by a computer, which produced the printout as the exercise progressed.

Simultaneously, the flow waveform of the respiratory cycle was measured at the exhalation and inhalation sides of the mouthpiece using two heated Fleisch meters (Gould Godart No 3) connected to

pressure transducers (Furness Controls FC001). Pressure and temperature measurements were made at the mouth using a third pressure transducer and a fast response thermocouple (Comark). The flow signals were sampled at 20 Hz, and stored for later analysis in a multichannel computer data logging system (developed at RLSD laboratories for use with an Apple microcomputer). The temperature and pressure measurements were sampled at 10 Hz and similarly stored.

DIFFERENCES BETWEEN CCBA AND THE MONITORING EQUIPMENT

The mouthpiece assembly differed in performance from a closed circuit breathing apparatus in that there was no provision for the simulation of a relief valve. A closed circuit breathing apparatus stores purified exhaled air in a breathing bag. A supply of oxygen is fed into the breathing circuit, to replenish the oxygen consumed by the wearer. If an excess of oxygen is supplied, as is usually the practice, the breathing bag completely fills, and the system pressurises. A relief or spill valve vents the excess oxygen to waste, causing a change to the pressure/flow characteristic of the apparatus. The frequency of operation and rate of flow through the relief valve depends on the severity of the work undertaken, the pattern of breathing of the wearer, and the oxygen flow rate into the apparatus. Each type of closed circuit breathing apparatus therefore produces a quite different relief valve characteristic, and a generalised simulation is impossible with an essentially open circuit method.

The **pressure/flow** characteristics of the relief valves of two types of CCBA are shown in Fig 1.

CALIBRATION

The vane **respirometer assembly** was calibrated by passing a succession of one litre pumps of air in and out of the **mouth tube** from a syringe prior to each **subjects'** program of exercises. Constant flows were also measured through the assembly to check the linearity and calibration of the Fleisch meters. The signal stored in the data logger is shown against true flow at room **temperature** in Fig 3. It shows that the response was linear for **exhalation**, and linear up to 150 **litres/min** for inhalation, above which a second straight line gave a good approximation. The one litre pulses produced by the syringe were checked for consistency with the constant flow calibration by integrating the pulses. The volumes were calculated to be within $\pm 1.5\%$ of the true value. This figure lies within 2 Least Significant Bits (LSB) divisions of the Analogue to Digital converters used on the data logging system. Since two Fleisch meters were used and logged separately, it is within 1 LSB for each instrument.

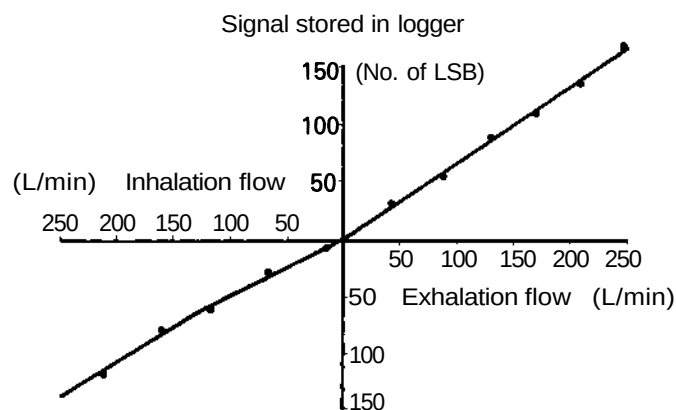


Figure 3. Mouthpiece Fleisch flow-meter calibration. (Laboratory air at 20°C.)

TEST PROGRAMME

The test programme for each subject consisted of a continuous treadmill walk at three work rates, performed in the order shown without a break between exercises. The exercises were

Exercise 1 6 kph on a level treadmill

Exercise 2 5 kph on a treadmill inclined at $7\frac{1}{2}^{\circ}$

Exercise 3 6 kph on a treadmill inclined at $7\frac{1}{2}^{\circ}$

The workrates were chosen to give expected minute volumes of approximately 40, 50 and 60 litres/min BTPS. Each exercise lasted approximately six minutes.

SUBJECTS

The subjects who performed the tests were all fit men aged between 21 and 44 years from the Mines Rescue Service in the NCB Scottish Area and were all experienced in the use of breathing apparatus.

DATA RECORDED

Complete data on all three exercises was recorded for 35 men. Four others could not complete the third, most severe exercise, either because they were fatigued, or because their heart rates were above 160 per minute, and judged to be too high, and the exercise terminated. Data from these four men was included for the analysis of the first two exercises, making 39 in total.

The data was edited to utilise only the last three minutes and twenty four seconds of data (equivalent to four kilobytes) to

ensure that the subjects minute volume had settled to his workrate. The settling period was monitored on the Morgan respiratory analyser, and was usually of about three minutes duration.

The flow data was collected in two halves; the inspired air was sampled at room temperature and humidity with one Fleisch meter, and the exhaled air at approximately Body Temperature and ambient Pressure Saturated (BTPS) with the second Fleisch meter.

To match the calibration gas, each **sample** half was converted to "laboratory" conditions of 20°C, ambient pressure, dry and the two halves summed into one continuous waveform. All figures and diagrams refer to flow at **these** conditions, unless otherwise stated.

Extracts of the waveforms of several **subjects** are given in Fig 4. As can be seen, each subject produced markedly different waveforms with different breathing frequencies, tidal volumes and shapes.

The respiratory gas exchange during these three minute periods were collected, and averaged for each exercise.

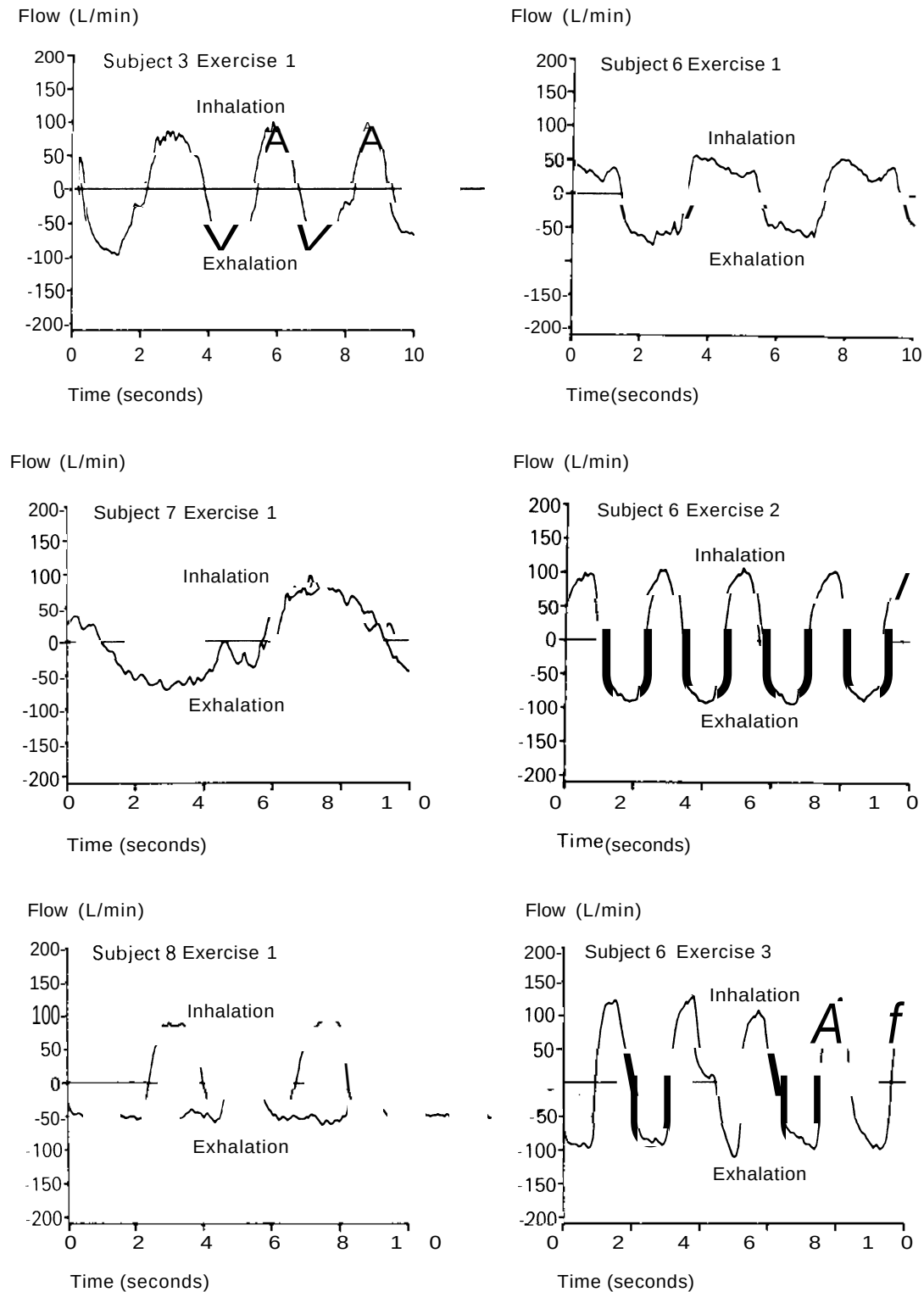


Figure 4. Samples of data showing consistency of shape within subjects and differences between subjects.

ANALYSIS OF WAVEFORMS - DISCUSSION

PREVIOUS METHODS OF ANALYSIS

The methods used by Silverman and Zechman to calculate the average breath were slightly different. Silverman recorded flow patterns photographically from a UV recorder, and measured the rise time to sustained flow, the time of sustained flow, the time of peak flow, and the time to fall from sustained flow to zero for each half of the breath. These factors were averaged, and the smoothest possible curve drawn through the resulting five points. The standard deviation breaths were produced by using the values of the points plus their standard deviations and scaling them to the average minute volume, tidal volume and maximum flow plus their respective standard deviations. This technique produced some rather odd standard deviation breath shapes at times.

Zechman et al divided each half breath into five equal time intervals, and the values of the flow in the intervals were averaged. This resulted in half breaths of six points, and a more complex shape was produced, however no patterns for the standard deviations of the breaths were produced.

These approaches had the disadvantage that different types of breath were combined with each other e.g. long drawn out breaths were combined with short sharp breaths. Any changes in the underlying pattern of short and long breaths was lost in the

averaging process. A check by eye of the data showed that short and long breaths did have different shapes.

FOURIER ANALYSIS METHOD

One commonly used method of analysing waveforms is to subject the data to a Fourier analysis, which produces a waveform containing the fundamental frequency and harmonics, so constructing the shape of the waveform within the fundamental. This method produces a single waveform, but suffers from the same drawback as the methods described previously, that is that different types of breath are combined, losing any structure that may exist amongst short and long breaths.

METHOD OF ANALYSIS FOR THESE EXPERIMENTS

The approach decided upon was to divide breaths into categories by breath length, and only combine and average breaths within each category, producing a series of averaged breaths ranging from the shortest to the longest. Subjects who breathe slowly and deeply tend not to be combined with subjects who breathe quickly, and any underlying change in the structure of their breaths is not lost.

Each breath recorded consists of an integer number of digitised points sampled at equal time intervals. The number of points determines which category the breath is to be classified in. The mean value of each equivalent point from all the breaths within

that category produces a category mean breath. Each point in the category mean breath therefore has a standard deviation associated with it.

The total population of breaths is therefore represented by a frequency distribution of the occurrence of each breath length. This is weighted by time by multiplying the number of breaths in each category by its duration, to produce distributions similar to those in Fig 5 (discussed more fully later). This is necessary to prevent short breaths being given more weight than long breaths because of their greater number per unit time. The breaths which correspond to the mean and any other quantile of these distributions can then be selected from the frequency distributions, and the shapes of these breaths can be examined.

The same analysis approach may be adopted for each individual subject, producing individual subject mean breaths and subject limit breaths, if the subject provides sufficient data. In view of the small amount of data produced by each subject, this has not been done for these experiments.

SELECTION CRITERIA

Several criteria for deciding what constitutes a valid breath were investigated. The selection of a breath from a continuous series of inspirations and exhalations may be made from one of two starting points:

- a) starting from zero flow, an inspiration, followed by an exhalation, and ending at zero flow.
- b) starting from zero flow, an exhalation, followed by an inspiration, and ending at zero flow.

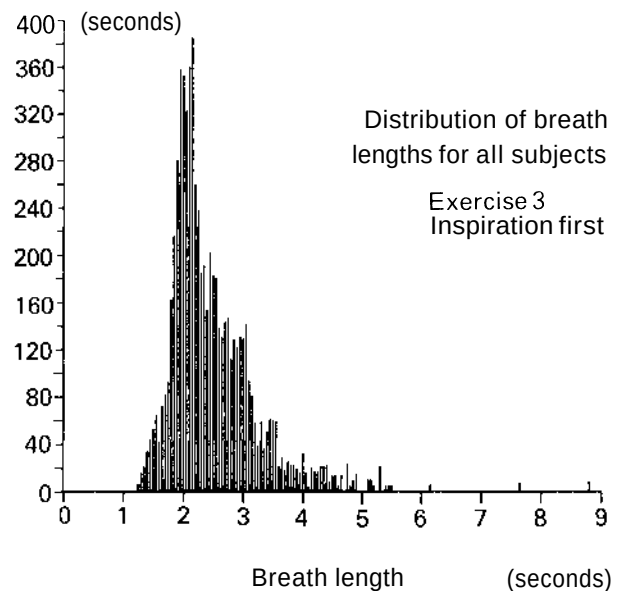
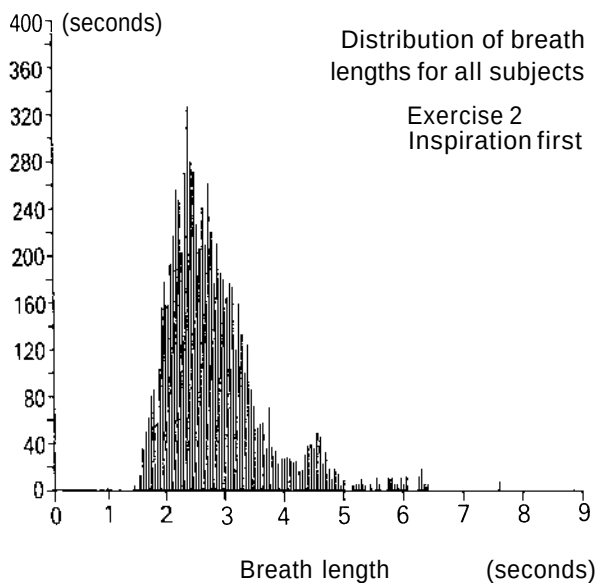
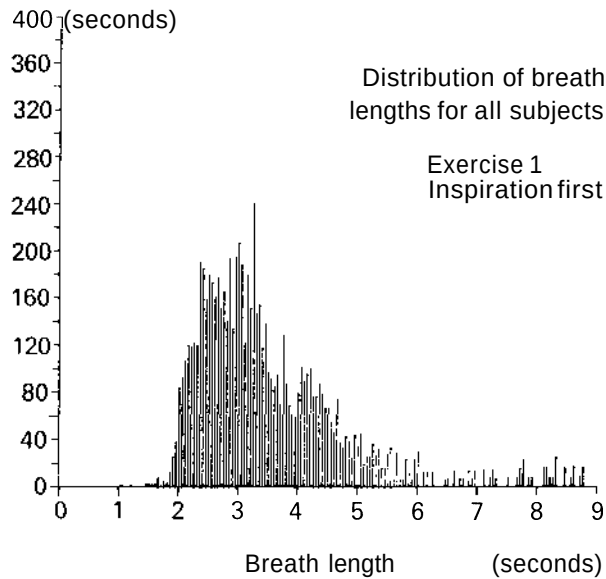


Figure 5. Time weighted frequency distributions of whole **breaths**, as selected with the inspiration phase first.

This assumes that the second phase of a breath is to be categorised along with the first, i.e. that the shape of a phase will affect the shape of the subsequent phase. If however, each phase is treated entirely separately then the two half breaths may be analysed separately into categories, each with its own frequency distribution. A whole breath may then be constructed from the averaged half breaths by matching quantiles of the two distributions at a point at which the tidal volumes of the two half breaths are the same.

The methods a) and b), although they allow the second phase to be grouped with the first phase, have the effect of invalidating the calibration. If two breaths of equal total length but different respiratory time ratio (RTR, equal to $T_E/T_{TOT} \times 100$) are averaged, there is a point at which the exhalation from one breath would be combined with the inspiration of another. The total phase volumes would be less than the sum of the two individual breaths phase volumes, and the shapes of the phases would be distorted at the cross-over. Therefore the categorisation of breaths was carried out with half breaths only.

REJECTION CRITERIA

Rejection criteria for double inhalations or exhalations caused by swallowing were identified by a similar process of checking the minimum length of a phase to that of Lind et al. (1984). They accepted a breath if a phase was longer than .1 second, only if the previous phase was longer than .3 seconds, and if inspiratory volume exceeded .14 litres or expiratory mouth pressure exceeded an unspecified value, depending on which phase was under consideration.

Since a certain amount of mouthpiece valve flutter was observed in these experiments it was found by trial and error that a breath should be rejected if the following conditions were met:-

- (i) First phase less than .15 seconds (noise in the signal)
- (ii) Second phase less than .45 seconds, but allowing the full .45 seconds to elapse before rejecting. This allowed a brief recrossing of the zero axis to allow for valve flutter and noise
- (iii) Inhalation or exhalation volumes less than .01 litres.

It was decided that valve flutter effects should be included in the measured waveforms because observation of the effect of the monitoring equipment on the man was the aim of the experiment.

Identification of breaths was found to be more reliable if the reference position was slightly above or slightly below zero flow. This ensured that breaths with inspiratory or expiratory pauses were classified into categories in a consistent fashion. The final choice of reference flow was equivalent to 7 litres/minute inspired, and the rejection criterion (iii) was introduced to ensure that the breath actually crossed the zero flow point.

The reference point level and the rejection criteria were developed by visually displaying each breath on the computer and following the computer rejection process by eye. Obviously 'good' breaths that were rejected or obviously 'bad' breaths that were accepted were identified, and the selection process refined.

The sample of data for each man for each exercise was processed in turn and two phase length frequency distributions and two sets of category mean phase breaths for each exercise were produced. The frequency distributions were weighted by time to produce distributions of the time spent by the subjects breathing at each rate, rather than distributions of the number of breaths at each rate.

The selection methods a) and b), although they cannot be used to produce category mean breaths, can be used to produce total breath length distributions. Fig 5 shows the breath length distributions, time weighted, obtained by selecting whole breaths using method a).

CATEGORY MEAN BREATHS

A category containing about 200 sample breaths was chosen at random. The data points in each equivalent sample in the category were inspected and all found to be normally distributed. The category phase mean breaths were therefore constructed using the arithmetic mean of each equivalent point from all the half-breaths in that category.

Figs 6, 7 and 8 show a selection of category mean breaths, with the standard deviations of each point, from each exercise. They were constructed as whole breaths by combining the appropriate half breaths from the equivalent (time weighted) quantiles from the frequency distributions of the half breaths.

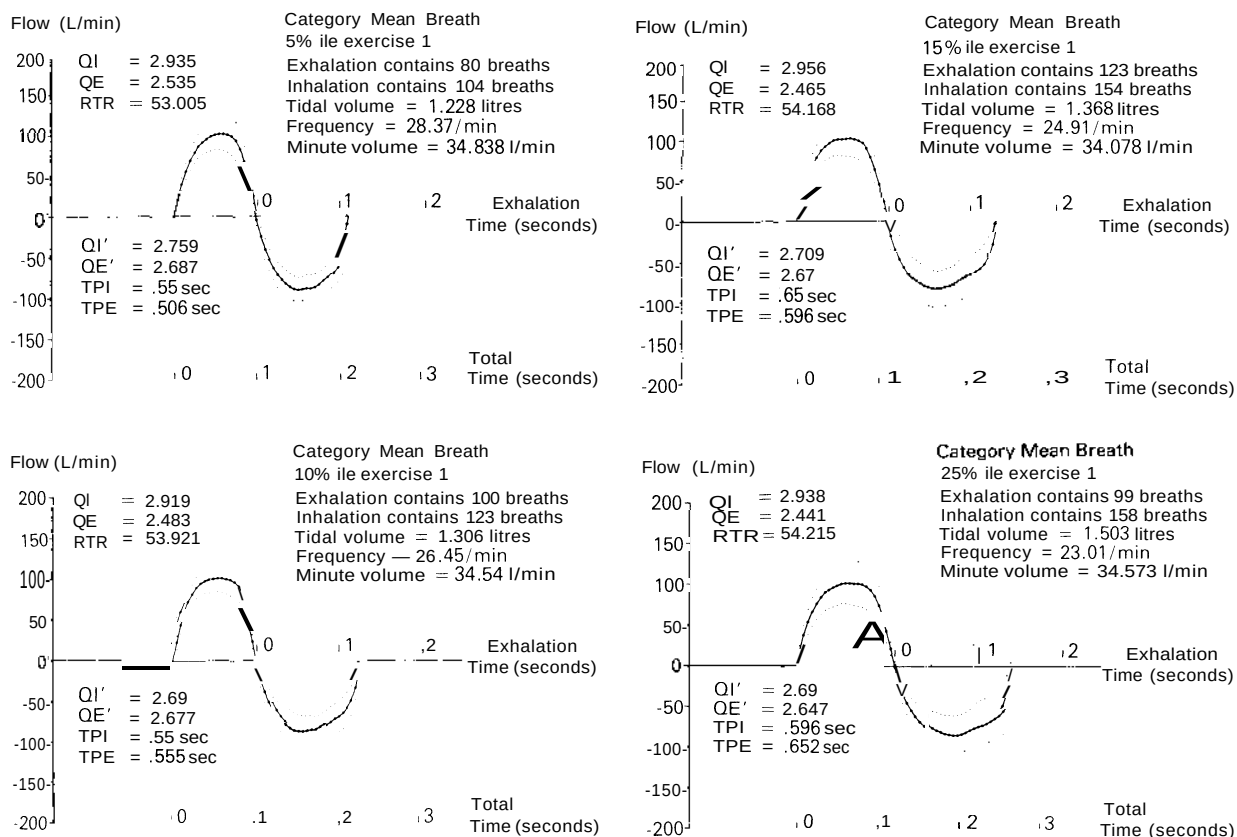


Figure 6a. Examples of the category mean breaths. The dots represent the standard deviations of each datum point.

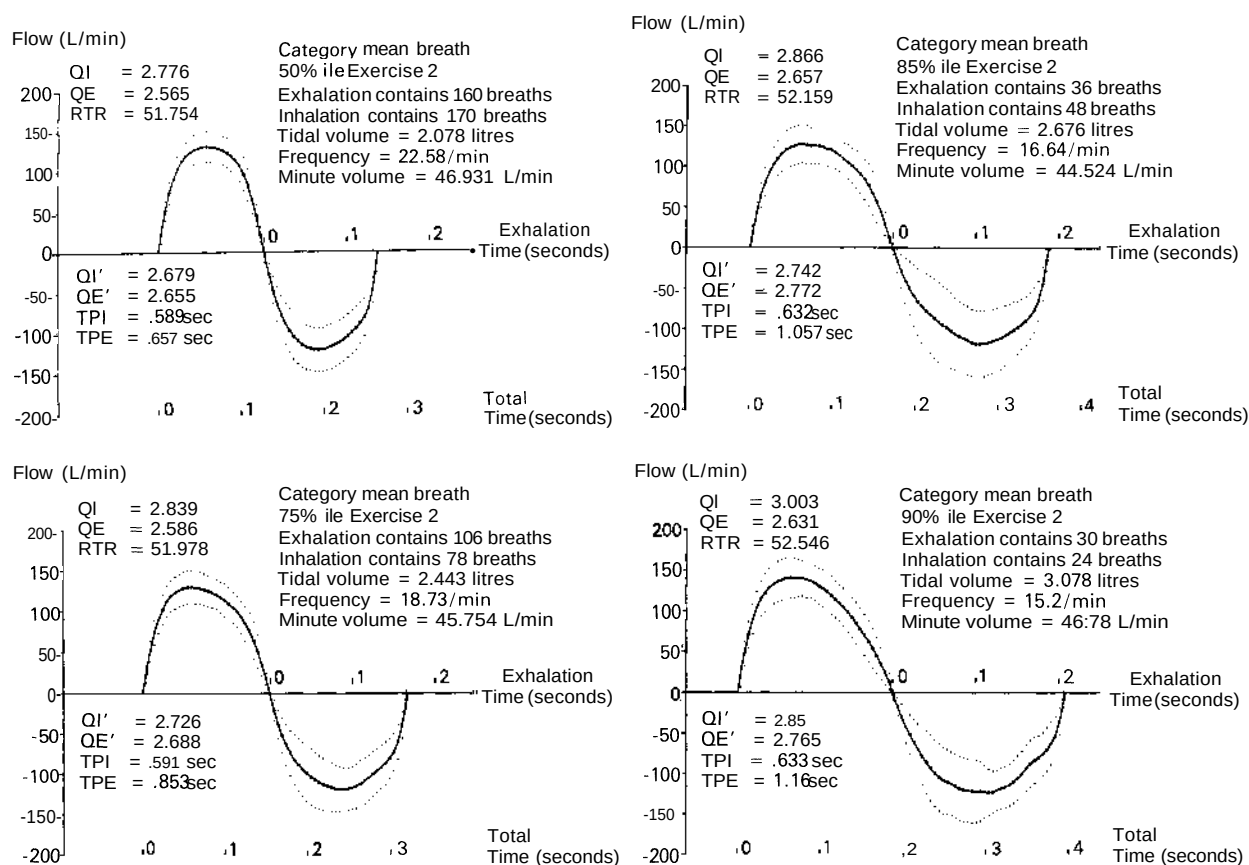


Figure 7b. Examples of the category mean breaths. The dots represent the standard deviations of each datum point.

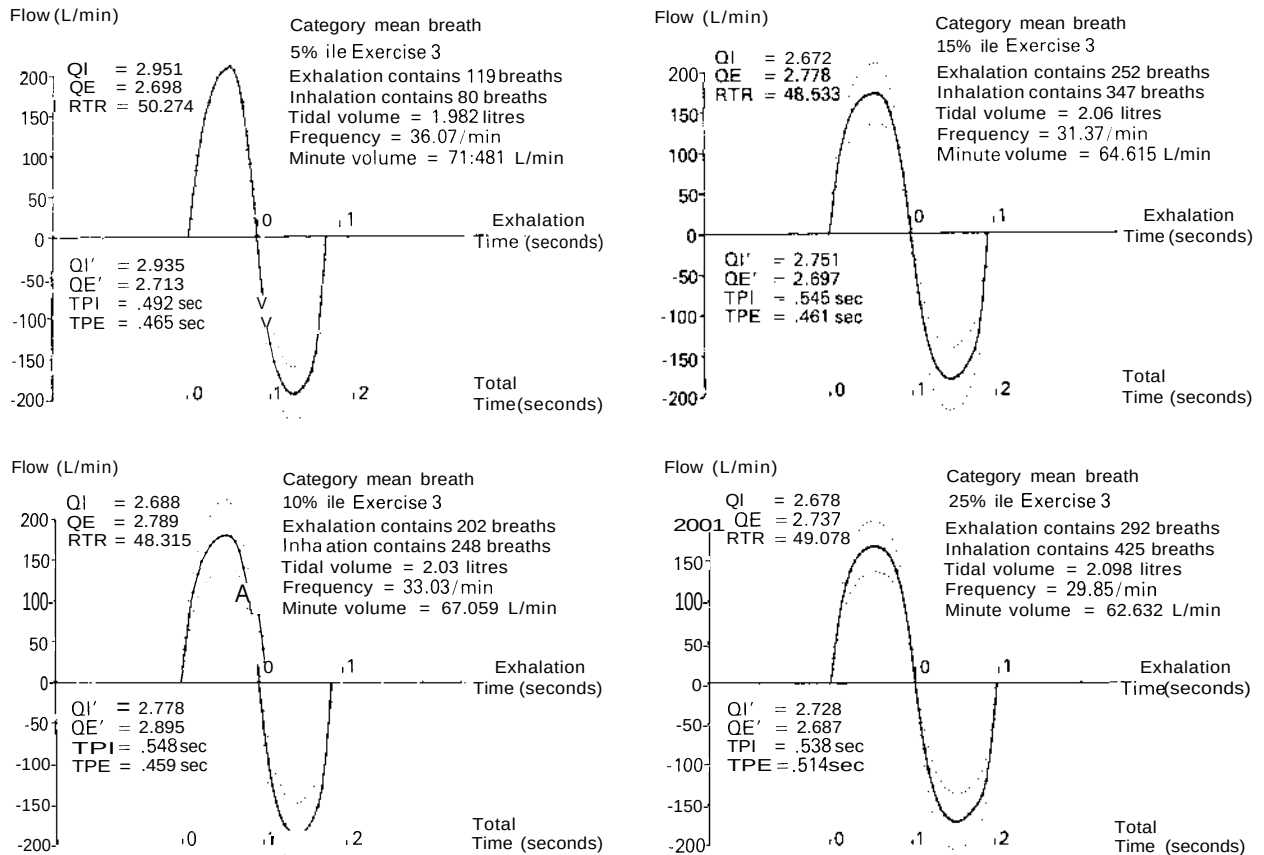


Figure 8a. Examples of the category mean breaths. The dots represent the standard deviations of each datum point.

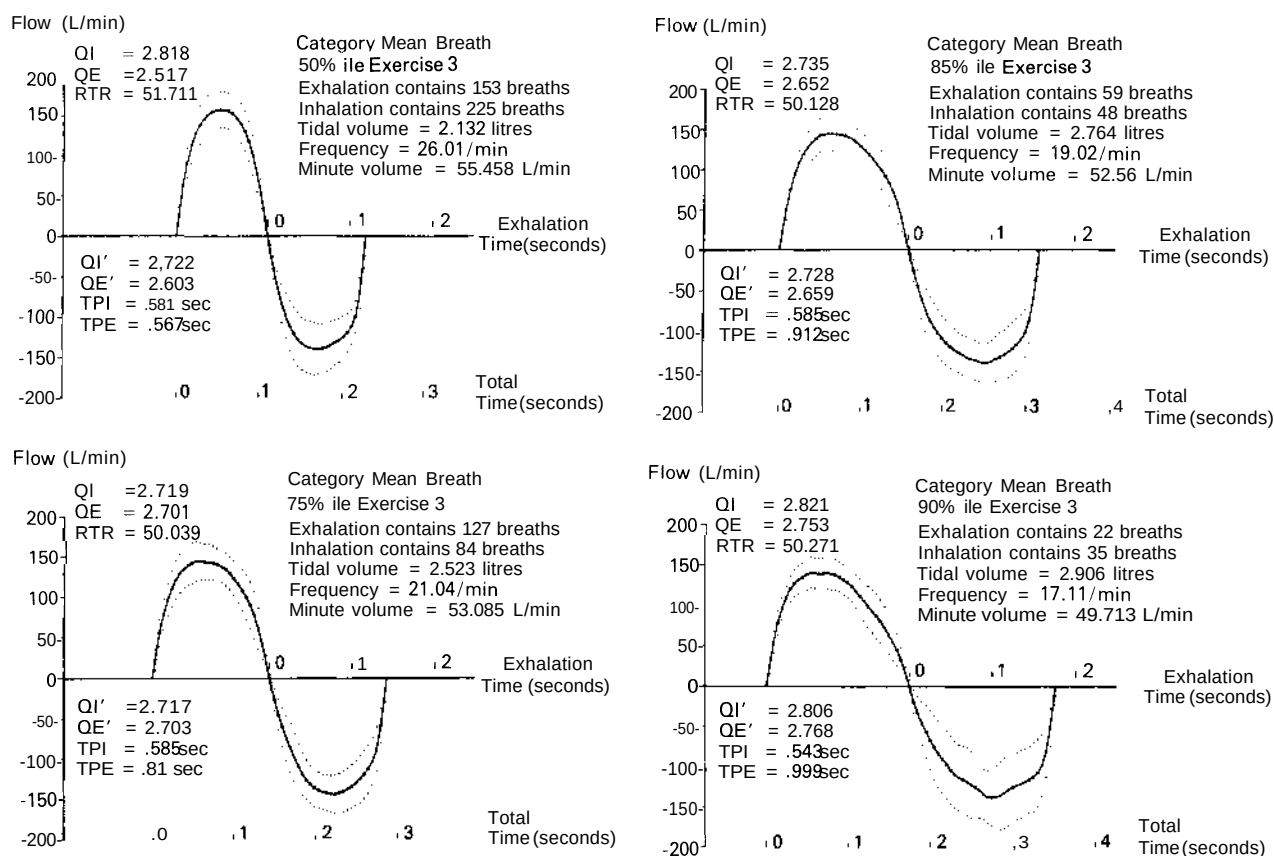


Figure 8b. Examples of the category mean breaths. The dots represent the standard deviations of each datum point.

The justification for this is that:

- (i) The quantile combined breaths are of similar length when compared to the equivalent quantile breath lengths selected from the whole breath distributions shown in Fig 5. Also they are similar to whole breath distributions using selection process b). The results are shown for comparison in Table I. It is only at the upper end of the distributions, where very few breaths fall into individual categories, that the distributions diverge.

TABLE 1

QUANTILES OF THE DISTRIBUTIONS OF COMBINED HALF BREATH LENGTHS COMPARED WITH WHOLE BREATH LENGTHS

Quantile (time weighted)	Combined Half Breaths Length (seconds)	Whole Breath Lengths Inspiration First (seconds)	Whole Breath Lengths Exhalation First (seconds)
EXERCISE 1			
2.5%	2.0 (102)(60) ^a	2.0 (45)	2.05 (40)
5%	2.1 (104)(80)	2.1 (52)	2.15 (53)
10%	2.25 (123)(97)	2.25 (54)	2.3 (56)
15%	2.4 (202)(115)	2.4 (81)	2.45 (72)
20%	2.5 (158)(122)	2.5 (73)	2.55 (70)
25%	2.6 (158)(98)	2.6 (63)	2.65 (62)
50%	3.2 (92)(94)	3.2 (48)	3.2 (47)
75%	4.15 (40)(39)	4.1 (22)	4.0 (23)
80%	4.4 (28)(23)	4.3 (20)	4.2 (23)
85%	4.75 (22)(29)	4.6 (10)	4.5 (17)
90%	5.3 (10)(9)	5.1 (4)	5.0 (7)
95%	6.5 (8)(2)	6.0 (5)	5.9 (2)
97.5%	7.5 (2)(4)	7.75 (3)	7.15 (3)

EXERCISE 2

2.5%	1.7 (71)(84)	1.75 (45)	1.75 (32)
5%	1.9 (124X111)	1.85 (30)	1.9 (40)
10%	2.0 (186)(169)	2.0 (90)	2.05 (84)
15%	2.1 (229)(169)	2.1 (95)	2.15 (99)
20%	2.2 (261X187)	2.2 (118)	2.25 (129)
25%	2.25 (261X199)	2.3 (88)	2.3 (107)
50%	2.65 (171)(160)	2.65 (91)	2.7 (86)
75%	3.2 (78)(106)	3.15 (55)	3.15 (66)
80%	3.4 (70)(59)	3.3 (41)	3.25 (34)
85%	3.6 (48)(36)	3.5 (21)	3.45 (23)
90%	3.95 (25)(30)	3.8 (9)	3.8 (14)
95%	4.6 (6)(10)	4.55 (11)	4.45 (8)
97.5%	5.25 (3)(7)	4.85 (4)	5.15 (2)

EXERCISE 3

2.5%	1.55 (83)(80)	1.55 (43)	1.55 (38)
5%	1.65 (80X119)	1.65 (45)	1.65 (44)
10%	1.8 (248X202)	1.85 (121)	1.85 (110)
15%	1.9 (347)(252)	1.9 (147)	1.9 (156)
20%	1.95 (347)(292)	1.95 (188)	1.95 (183)
25%	2.0 (425X292)	2.0 (176)	2.0 (195)
50%	2.3 (225X153)	2.3 (80)	2.3 (80)
75%	2.85 (84)(127)	2.85 (46)	2.8 (49)
80%	2.95 (62)(73)	2.95 (45)	2.95 (34)

TABLE 1 Continued

85%	3.15	(48)(59)	3.1	(30)	3.1	(38)
90%	3.5	(24)(32)	3.45	(18)	3.3	(17)
95%	4.0	(7)(9)	3.5	(4)	3.85	(4)
97.5%	4.5	(7)(7)	4.45	(2)	4.45	(8)

a The **numbers** in **brackets** after the breath length refer to the number of breaths within the category breath length. There are two **numbers** in brackets after the **combined** half breaths lengths, **because** there are different numbers of samples in the two individual half breath categories from which the quantiles have been **selected**.

(ii) The tidal volumes of the two equivalent quantile mean half **waveforms** are similar, producing an error in the combined breath typically equivalent to less than 1 LSB zeroing error from the logging **system**.

(iii) The tidal volumes of the quantile mean breaths have a **monotonic**, though not necessarily linear, relation to breath length. Thus there is only one category with the **matching volume**.

The two half waveforms were combined into one by simply placing the exhalation next to the inspiration, and the exact position of the zero flow chosen inside the ± 1 LSB band so as to equalise the two half waveform volumes. This ensured that the waveform which would be reproducible on a variable waveform breathing simulator. The exact length of the breath was estimated by extending the straight line from the second data point to the first data point and down to the zero flow axis to find the start of the breath, and by using a similar procedure on the last two points to find

the end. The breath lengths shown in Figs 6, 7 and 8 are therefore not integer numbers of data points, as in Table I, but extrapolations between the integers.

It is interesting to note that no sign of valve flutter can be seen in the category mean breaths. It has been lost in the averaging process.

FACTORS DESCRIBING WAVEFORMS - DISCUSSION

Having obtained three series of category mean breaths there must be characteristics picked from the breaths to define their "shapes".

Q FACTOR AND RTR

One commonly used index is the shape factor Q, essentially a "sharpness" factor. Each phase of the waveform requires a Q factor, hereafter called QI and QE, defined as the peak flow in the appropriate phase divided by the overall average flow (in this case, the minute volume). For a square or symmetric rectangular waveform, the Q factor can be shown to be 2. For a sinusoidal waveform, the Q factor is π . For a triangular waveform, the Q factor is 4, see Appendix 2.

If the Q factors are corrected for RTR, that is $QI' = QI \times (100 - RTR)/50$ and $QE' = QE \times \frac{RTR}{50}$, then $QI' = QE' = 4$ for all RTR and the shape factor Q' will identify the underlying shape of each phase consistently.

If this factor is applied to the results mentioned previously, then Silverman produced QI' from 3.6 at rest to 2.8 at high work-rates, and QE' from 3.1 falling to 2.8.

Bentley et al produced values of QI' of $2.85 \pm .17$ and QE' of $2.34 \pm .05$.

TIME OF OCCURRENCE OF PEAK FLOW

The two indices Q' and RTR are Insufficient to identify a basic shape since the position of maximum flow in the phase must be located. A new factor Tp is introduced, defined as the time from the beginning of a phase at which the peak occurs. Each phase requires a Tp factor, hereafter called Tp_I and Tp_E . Tp is defined as a time rather than as a proportion of breath length because it is a more useful measure, as will be shown later.

FACTORS DESCRIBING WAVEFORMS - RESULTS

CATEGORY MEAN BREATHS

As explained above (Method of Analysis for these Experiments), the category mean breaths for each percentile of the frequency distributions can be calculated. The factors describing the category mean breaths are shown for each exercise in Figs 10 a to c as scatter plots for each factor. Each point is the mean of all the breaths in the category in which the quantile occurs. Since the distributions are time weighted, there are many more samples in the shorter categories than the longer ones (see Table I). The scatter is more apparent therefore at the longer breath categories which may contain only 6-7 breaths, than the shorter categories, which may contain over 100.

Q Factors

QE is typically 2.4 to 3, rising slightly with exercise rate shown in Fig 10a. There seems to be a minimum at $T_E = 1.2$ to 1.4 seconds. QE is higher, typically 3.2 to 2.6, falling with exercise rate. Again there seems to be a minimum at $T_I = 1.2$ seconds.

Correction for RTR produces QE' and QI' which have equal values for each phase and which show no variation between exercise rates. QE' and QI' are typically 2.6-2.8, with only extremely long breaths rising above 2.8. The minima are again seen at T_E and $T_I = 1.2$ to 1.4 seconds.

The bulk of the breaths are represented by the points at the minima of the plots, so for each exercise, QI' and QE' are in general 2.6 to 2.7. Minimising Q' , i.e. reducing the peak flow in the breath, reduces the respiratory work over the breathing cycle.

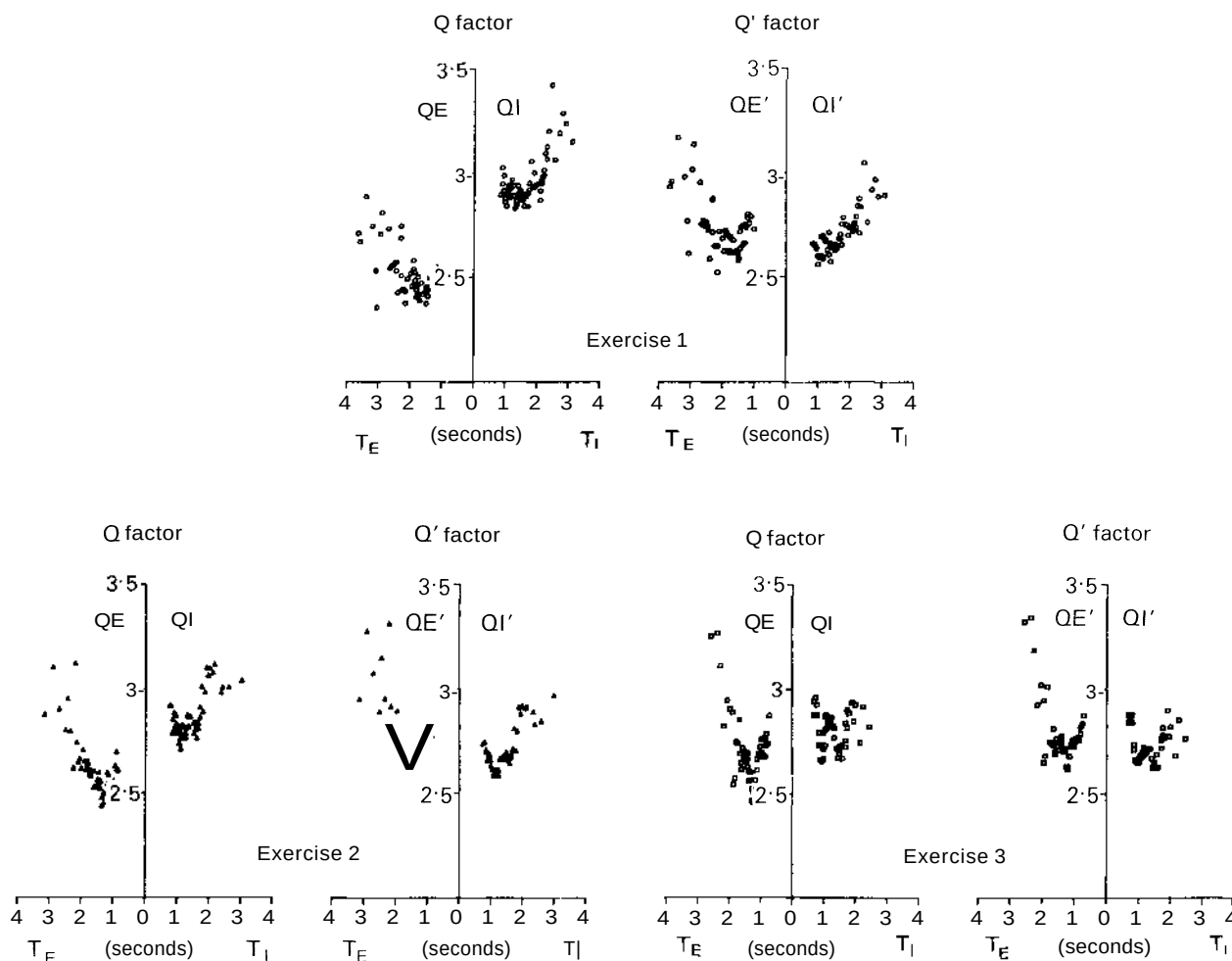


Figure 10a. Scatter plots of the factors of the percentile category mean breaths.

RTR

The respiratory time ratios of the quantile category mean breaths are shown in Fig 10b. This shows that RTR is fairly constant for all breaths at each exercise, but diminishes from 52%-54% at the

lower workrate to 50%-52% at the higher workrate, agreeing with the results of Clark and von Euler and Gardner. The apparent structure is due to the integer numbers of data points in the breaths.

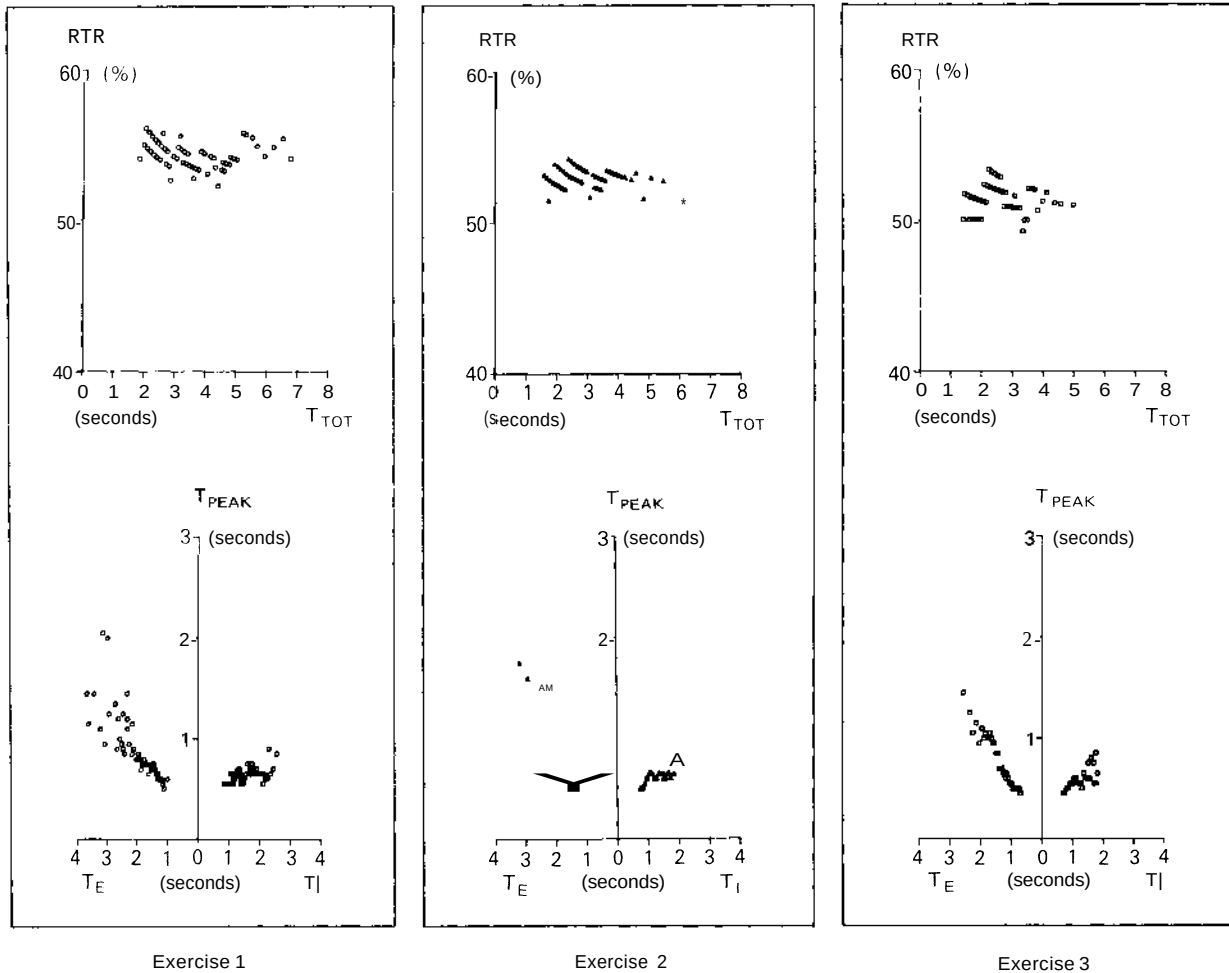


Figure 10b. Scatter plots of the factors of the percentile category mean breaths.

Peak Flow

The peak flow factors T_{PI} and T_{PE} for the quantile mean breaths are also shown in Fig 10b. They show that T_{PE} is linearly related to T_E , i.e. that the peak occurs at approximately the same proportion of the phase length, approximately 50%. T_{PI} however,

varies little with breath length or exercise, the bulk of the points occurring at T_{PI} of approximately 0.6 seconds. This may be seen by examining the shapes of the quantile mean breaths in Figs 6, and less obviously in Figs 7 and 8. The peak of the inspiration of the 5%ile breath occurs to the right of the phase. As the breath length increases, the inspiration becomes symmetrical, and eventually skews to the left. The exhalation phase develops a shoulder to the right, the first part of the phase maintaining a constant shape in proportion with the length of the breath. The shapes of the higher quantiles break down as the number of samples in a category become fewer, and the effects of signal noise are seen more clearly.

Tidal Volume and Minute Volume

The tidal volumes of the quantile category mean breaths are shown in Fig 10c. At each workrate, V_T increases and T_{TOT} , T_I and T_E shorten in a linear relationship, as found at higher workrates by Gardner. The V_T/T lines cross the V_T axis at a higher value of V_T for higher workrates. This agrees with Newsome, Davis and Stagg, who measured V_T/T for resting subjects, the regression line crossing the V_T axis slightly above the origin.

The minute volume decreases with increased breath length. There appears to be a two stage slope to the $\dot{V}/T_{TOT}$ plot suggesting that V_T is not quite linear with T , however it is impossible to fit a least squares regression to these lines because of the different numbers of breaths contained within each point.

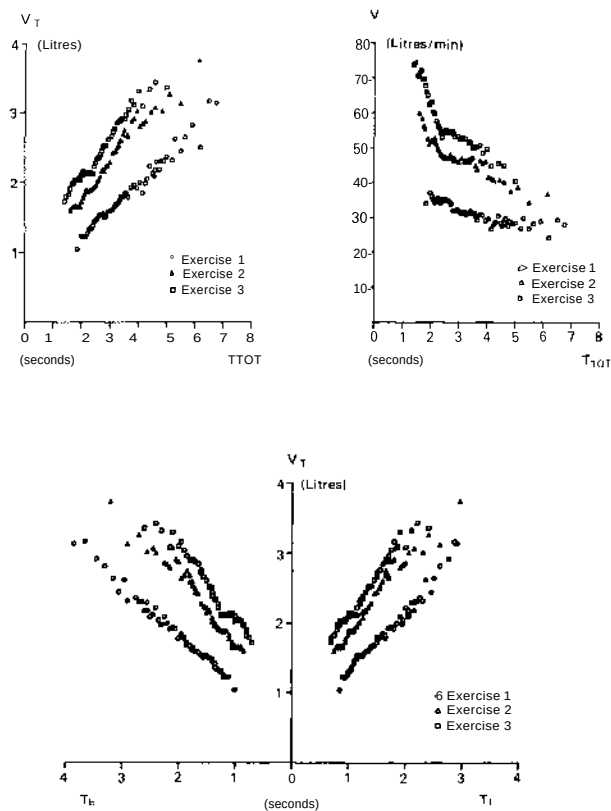


Figure 10c. Scatter plots of the factors of the percentile category mean breaths.

ANALYSIS OF INDIVIDUAL BREATHS

The factors of the breaths may be calculated for each individual breath. This has been done for whole breaths defined as an inspiration followed by an exhalation for the same data from which the category mean breaths were derived, using the same decision and rejection criteria. In this analysis, there was no reason to suppose that the volume exhaled would be similar to the volume inhaled in an isolated breath, and therefore no zero flow line was interpolated to balance the volumes. Specimen results of the factors are shown as scatter plots Fig Ha to c together with linear regression lines where appropriate. The factors and regressions are summarised in Table 2.

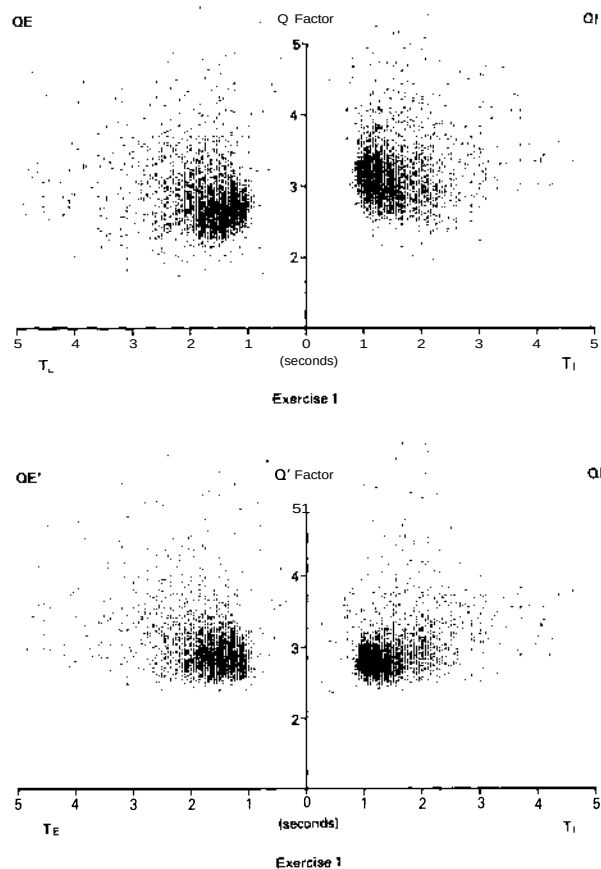


Figure 11a. Examples of the scatter plots of the factors for individually analysed breaths, as selected with the inspiration first.

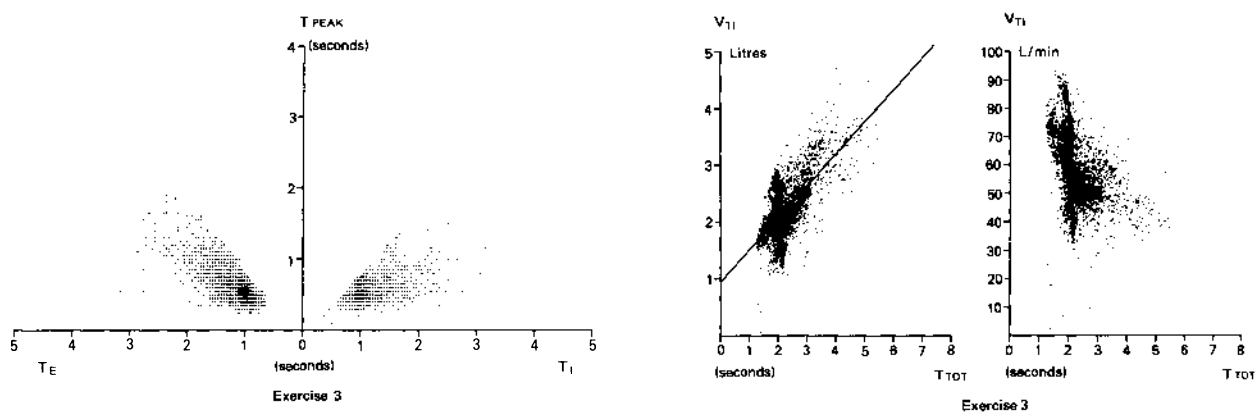


Figure 11b. Examples of the scatter plots of the factors for individually analysed breaths, as selected with the inspiration first.

TABLE 2

Regression lines of best fit of breath factors obtained from individual breaths, inspiration phase chosen first at laboratory conditions.

Equation of the form $y = A + Bx$.

EXERCISE 1 2414 Breaths

Factors y / x	A *std error	B ±std error	Significance of fit (prob. $y = y$)	$\bar{y}$ *std error	Correlation co- efficient
V_{TI}/T_I	.432±.022	.822±.014	$p < .025$	1.648±.011	.77
V_{TE}/T_E	.490±.027	.697±.015	$p < .025$	1.676±.012	.69
V_{TI}/T_T	.418±.025	.387±.008	$p < .025$	1.648±.011	.72
V_{TE}/T_T	.368±.026	.411±.008	$p < .025$	1.676±.012	.73
T_{PI}/T_I	.408±.012	.164±.008	$p < .05$	.650±.024	.39
T_{PE}/T_E	.164±.018	.367±.010	$p < .025$	.788±.007	.59
$(T_I/T_{PI})/T_I$	.91 ±.05	1.02 ±.03	$p < .025$	2.42 * .02	.56
$(T_E/T_{PE})/T_E$			n.s	2.43 ± .03	
$(T_{PE}/T_E)/T_E$			n.s	.470±.003	
Q_I/T_I			n.s	3.204±.012	
Q_I'/T_I			n.s	2.938±.007	
Q_E/T_E			n.s	2.848±.014	
Q_E'/T_E			n.s	3.012±.009	
RTR/T_T			n.s	53.6 ± .1	
$\dot{V}_I/T_T$			n.s	31.4 ± .2	
$\dot{V}_E/T_T$			n.s	31.9 * .2	

$$\bar{T}_I = 1.48 \pm .01$$

$$\bar{T}_E = 1.70 \pm .01$$

$$\bar{T}_T = 3.18 \pm .02$$

TABLE 2 continued

EXERCISE 2 2960 breaths

Factors y / x	A *std error	B ±std error	Significance of fit (prob. $y = \bar{y}$)	$\bar{y}$ ±std error	Correlation coefficient
V_{TI}/T_I	.676±.025	1.100±.019	p<.025	2.086±.010	.73
V_{TE}/T_E	.829±.031	.935±.022	p<.025	2.108±.010	.62
V_{TI}/T_T	.633±.029	.548±.011	p<.025	2.086±.010	.69
V_{TE}/T_T	.651±.030	.550±.011	p<.025	2.108±.010	.68
T_{PI}/T_I	.384±.010	.179±.007	p<.05	.613±.003	.42
T_{PE}/T_E	.039±.014	.488±.010	p<.025	.706±.005	.675
$(T_I/T_{PI})/T_I$	.85 ±.09	1.04 ±.03	p<.025	2.175±.013	.56
$(T_E/T_{PE})/T_E$			n.s	2.074±.012	
$(T_{PE}/T_E)/T_E$			n.s	.518±.003	
Q_I/T_I			n.s	2.981±.008	
Q_I'/T_I	2.54 ±.02	.253±.015	p<.05	2.860±.006	.29
Q_E/T_E			n.s	2.779±.007	
Q_E'/T_E	2.42 ±.02	.314±.014	p<.05	2.853±.006	.38
R_{TR}/T_T			n.s	51.7 ±.1	
$\dot{V}_I/T_T$	58.9 ±.7	-4.21 ±.25	p<.05	47.6 ±.2	.29
$\dot{V}_E/T_T$	59.8 ±.7	-4.38 ±.25	p<.05	48.1 ±.2	.31
$\bar{T}_I = 1.282±.007$					
$\bar{T}_E = 1.367±.007$					
$\bar{T}_T = 2.649±.013$					

TABLE 2 continued

EXERCISE 3 3013 breaths

Factors y / x	A ±std error	B *std error	Significance of fit (prob. y = y)	$\bar{y}$ ±std error	Correlation co- efficient
V_{TI}/T_I	.969±.025	1.100±.021	p<.025	2.235±.009	.69
V_{TE}/T_E	1.104±.029	.981±.024	p<.025	2.253±.009	.60
V_{TI}/T_T	.961±.028	.549±.012	p<.025	2.235±.009	.65
V_{TE}/T_T	.957±.028	.558±.012	p<.025	2.253±.009	.65
T_{PI}/T_I	.314±.009	.227±.007	p<.05	.574±.003	.49
T_{PE}/T_E	.034±.011	.516±.009	p<.025	.638±.004	.72
$(T_I/T_{PI})/T_I$	.91 ±.03	1.00 ±.03	p<.025	2.065±.011	.56
$(T_E/T_{PE})/T_E$			n.s	1.92 ±.01	
$(T_{PE}/T_E)/T_E$			n.s	.546±.002	
QI/T_I			n.s	2.906±.006	
QI'/T_I			n.s	2.864±.005	
QE/T_E			n.s	2.840±.007	
QE'/T_E	2.520±.017	.278±.014	p<.05	2.846±.005	
RTR/T_T			n.s	50.44 ±.07	
V_I/T_T	80.0 ±.8	-9.14 ±.32	p<.05	58.6 ±.2	
V_E/T_T	80.6 ±.8	-9.20 ±.33	p<.05	59.0 ±.2	
$\bar{T}_I = 1.151 \pm .006$					
$\bar{T}_E = 1.171 \pm .006$					
$\bar{T}_T = 2.322 \pm .011$					

Q Factors

Fig Ha does not show clear minima for Q1 and QE at T = 1.2 seconds as seen for the quantile category means **because** of the random scatter of the points. The centres of the densest parts of the scatters occur at T ~1.2 seconds.

The mean value of QE is 2.85, and is constant over the exercises.

The mean QI is 3.2 in exercise 1 falling to 2.9 in exercise 3.

The mean values of QI' and QE' are 2.85 to 3.0, and do not vary with exercise rate. The minimum value seen of QI' or QE' from any breath is 2.4, whereas QI and QE on occasion drop below 2.0. This suggests that they are flatter than a rectangular waveform but arises because of the effect of RTR on Q.

The mean values of the Q factors are higher than those in the quantile mean breaths. This is because the flow measured in an individual breath will contain noise, and consist of small peaks and troughs overlaying an overall waveform. The Q factor, being obtained from the peak flow, will include the noise value of a peak and be artificially high for a smooth waveform. In the quantile mean breath, the noise will have been reduced, and the Q factors are lower.

RTR

The mean RTR for exercise 1 is 53.6%, falling to 50.4% in exercise 3, agreeing closely with the quantile mean breaths.

Peak Flow

The individual T_p plots (Fig 11b) show fits to a straight line which are not seen in the quantile mean plots. This is because T_{pI} and T_{pE} are limited to values less than T_I and T_E . The

scatter is confined to a triangular section of the graph, which is seen as a regression by a least squares analysis.

In order to test the hypothesis that T_{PI} is a constant, the ratio T_I/T_{PI} should be linear with T_I . The linear regression is shown in Table 2, a confidence of .975 being produced in each exercise.

In order to test the hypothesis that T_{PE} is a constant proportion of T_E , the ratios T_E/T_{PE} and T_{PE}/T_E should both be constants independant of T_E . The linear regressions of these are shown in Table 2. For each exercise, both the regressions yielded non-significant results, supporting the hypothesis that T_{PE} is proportional to T_E .

Tidal Volume and Minute Volume

The scatter plot of V_{TI}/T_{TOT} of exercise 1 is shown in Fig 11b. The same regression straight line is superimposed on the quantile mean scatter plots of V_T/T_{TOT} in Fig 12, together with the other two exercises. This shows that the quantile mean breath volumes and the individually analysed breath volumes match closely. V_{TE} and T_{TOT} show a similar close match but are not shown on Fig 12 for clarity.

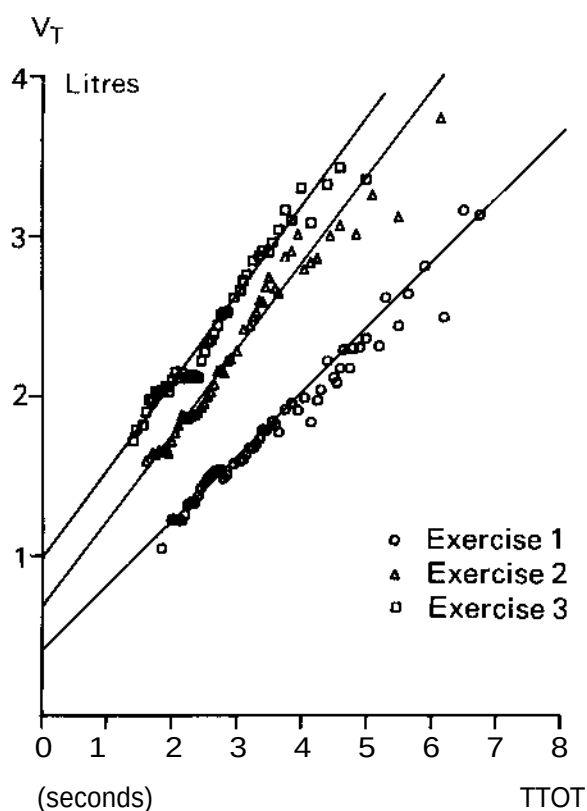


Figure 12. Best linear least squares fit from the individually analysed breaths superimposed on the scatter plot of the percentile category mean breaths.

CHOICE OF FACTORS TO PICK A MEAN BREATH FOR EACH EXERCISE

The analysis of individual breaths has been shown to be described by a set of factors which closely match the quantile category mean breath set of factors, the differences between the two sets being explained.

The values of the factors of a mean breath may be chosen by selecting the mean values of the factors from the analyses of the individual breaths, but this does not necessarily imply that the mean breath contains all these properties. In fact, the mean

values may not necessarily produce a valid breath. This is because some of the factors are more appropriately described by a linear regression rather than a simple mean, see Table 2. The mean values of the individual factors are summarised in Table 3. The factors of the 50% ile category mean breaths are also shown in Table 3. Although the factors have been shown to be similar, the mean values of the factors do not completely match the factors of the 50% ile breath. Examination of Table 3 shows that the minute volume of the 50% ile category mean breath is lower than the mean minute volume, and the tidal volume is also slightly lower. However, the quantile category mean volume rises as minute volume falls, therefore there is no quantile mean which **matches** both individual mean figures exactly. The best estimates of the mean breath **parameters** are given by the 50% ile category mean breath in all three exercises. In order to reproduce these breaths on a variable waveform breathing simulator, the values of the points within the category are quoted in Appendix 1, and shown together with the standard deviations of each point in Figs 6, 7 and 8.

In order to submit a breathing apparatus to a representative breathing pattern of a man, several of the quantile category mean breaths could be used for a short period in turn, rather than a single waveform used continuously. As a simple example, the deviation limit breaths, say the 15%ile and the 85%ile, could each be used for 25% of the time, and the 50%ile for the remaining 50%.

TABLE 3

Mean Factors for Each ExerciseIndividual breaths

Exercise	$\dot{V}$ (l/min) lab.	V_T (litres) lab.	T_I (sec)	T_E (sec)	T_{TOT} (sec)	RTR (%)	T_{PI} (sec)	T_{PE} (sec)	QI	QI'	QE	QE'
1	31.6	1.66	1.48	1.70	3.18	53.6	.65	.79	3.20	2.94	2.85	3.01
2	47.8	2.10	1.28	1.37	2.65	51.7	.61	.71	2.98	2.86	2.78	2.85
3	58.8	2.25	1.15	1.17	2.32	50.4	.57	.64	2.91	2.86	2.84	2.85

Best category mean breath (50%ile)

1	31.3	1.67	1.46	1.75	3.21	54.6	.55	.745	2.93	2.66	2.47	2.70
2	46.8	2.08	1.29	1.37	2.66	51.7	.59	.66	2.77	2.68	2.57	2.65
3	55.5	2.13	1.11	1.19	2.31	51.7	.58	.57	2.82	2.72	2.52	2.60

Estimated errors in the measurement of the factors

<u>+1.0</u>	.04	.05	.05	.1	1	.05	.05	.05	.05	.05	.05	.05
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TABLE 3 continued

Data From Respiratory Analyser over Approximately the Same Intervals

Exercise	$\dot{V}$ l/min BTPS	V_T litres BTPS	$\dot{V}$ l/min lab.	V_T litres lab.	exhaled CO ₂ (%)	exhaled O ₂ (%)	production of CO ₂ ml/min STPD	consumption of O ₂ ml/min STPD	RQ
1	34.3	1.99	29.6	1.71	4.59	15.22	1250	1649	.76
2	55.0	2.56	48.6	2.18	4.94	15.14	2146	2597	.83
3	68.3	2.73	58.6	2.36	4.92	15.36	2644	3041	.87

The respiratory exchange data from the respiratory analyser is also shown in Table 3. The results have been averaged for the approximate time intervals during which the waveforms were analysed, but are not exact because only minute to minute printouts were available. This may account for some of the discrepancy between the minute volumes and tidal volumes produced from the Fleisch meters, and those from the turbine flowmeter of the respiratory analyser. In addition, errors may have been introduced in the correction of temperatures and pressures to laboratory conditions. The assumption that the exhaled air was measured at BTPS may not be exact even though the exhalation Fleisch meter was thermostatically controlled to 37°C.

The respiratory analyser computed the results by accumulating an integer count of the number of breaths detected in a **minute**, and computing the tidal volumes from this integer. Since a **non-**integer number of breaths occurred in one **minute**, a certain amount of error has been introduced by only examining isolated minute periods. The lower breathing frequencies were more sensitive to integerising errors, and a slightly high tidal volume result was probably produced. The effect diminishes with a longer **experiment**.

CONCLUSIONS

A method to obtain average breathing waveforms has been developed, improving on the previous methods of analysis. Deviation limit breaths may be directly selected from the distribution of quantile mean breaths. Factors describing the waveforms have been discussed and new factors QI' and QE' introduced to eliminate RTR from consideration of an individual phase; typically QI' and QE' are 2.6 to 2.7. T_{PI} and T_{PE} have been introduced to define the skewness of the peak of the waveform. T_{PI} is constant at about 0.6 seconds; T_{PE} varies, being approximately 50% of phase length. The average breaths have the properties shown in Table 3. The breaths may be programmed into a variable waveform breathing simulator by constructing smooth waveforms from the points quoted in Appendix I. These are only the 50%ile breaths, however, and a more realistic simulation of a breathing pattern would use a range of breaths.

The method to obtain the waveform may be improved upon. The extrapolation to zero flow from the first point of a breath and last point may be improved by retaining the previous data point, and subsequent data point, and discarding the fraction below (or above) zero flow. This would improve the estimate of the length of the breath. The rejection criteria could be altered to improve the quality of the selected breaths by increasing the minimum volume limit.

APPENDIX 1

Flow data points of the 50 percentile category mean breaths in litres/minute at laboratory conditions at 0.05 second intervals, with the inspiration positive

Exercise 1

18, 35.9, 49.6, 60.4, 70, 76.9, 81.7, 85.6, 88.6, 90.5, 91.7, 91.6, 91.4, 91.4, 91.1, 90.4, 89.5, 88.1, 86.3, 83.8, 80.8, 77, 72.4, 66.2, 57.9, 46.8, 33.4, 17.6, 1.4, -13, -24.2, -34.5, -42.9, -49.5, -55.9, -61, -65.6, -69.3, -71.9, -74.2, -75.6, -76.4, -77, -77.1, -76.9, -76.1, -74.8, -74.1, -73, -71.2, -69.4, -67.3, -65.2, -63.4, -61.4, -58, -54.9, -52.4, -50.1, -46.5, -41.5, -34.4, -21.4, -2.9

Exercise 2

22.6, 51.4, 73.5, 90.5, 103.1, 112.2, 119.1, 123.4, 126.4, 128.5, 129.8, 130.3, 130.2, 129.3, 127.8, 125.5, 122.5, 118.4, 113, 106.1, 96.4, 82.9, 65.6, 45.5, 21.7, -3.7, -26.8, -46.9, -63.7, -77.5, -88.3, -97.2, -104.4, -109.8, -114.3, -117.3, -118.9, -120, -120.3, -119.9, -118.4, -116.5, -114.3, -111.2, -107.8, -103.7, -99.3, -94.2, -88, -80.7, -69.6, -47.8, -12.6

Exercise 3

24, 62.5, 90.8, 111.8, 127.3, 137.5, 144.6, 149.9, 153.9, 155.8, 156.3, 156.3, 155.2, 151.8, 146.6, 139.9, 130.5, 117.5, 99.8, 78, 52.6, 21, -11, -39.3, -63.4, -83.1, -98.7, -110.8, -120.5, -127.9, -133, -136.2, -138.2, -139.5, -139.4, -139, -137.5, -134.6, -131.5, -128.4, -124.4, -119.2, -112.2, -99.5, -70.3, -23.7

ACKNOWLEDGEMENTS

The enthusiasm and co-operation of the Scottish Area Mines Rescue personnel and the assistance of Mr Gordon Smith and Mr Alan Johnson of NCB Scientific Control, Corstorphine, Edinburgh in carrying out the experiments, is gratefully acknowledged.

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