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THE EFFECT OF THE RATE OF BREATHING ON THE MAXIMUM BREATHING CAPACITY DETERMINED WITH A NEW SPIROMETER

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Very few quantitative observations have been reported on the effect of rate of breathing on the voluntary maximum breathing capacity (M.B.C.). Proctor and Hardy (1949) found that the M.B.C. was achieved at a rate of 30 respirations per minute (R.P.M.). At higher rates of breathing the ventilatory capacity was diminished. These observations are contrary to the findings of other investigators who regard a fast rate of breathing as essential in producing the largest value for the M.B.C. (Gray and Green, 1945; Baldwin, Cournand, and Richards, 1948). None of these investigators used spirometers which had been tested for recording errors (Bernstein and Mendel, 1951), nor were the observations made at controlled rates of breathing.

The effect of rate of breathing on the M.B.C. of a group of normal subjects has been investigated. This work has been performed on a spirometer which is substantially free from recording error. It has been suggested that to control the rate of breathing impairs the subject's performance, but evidence is provided here to show that there is no sound basis for that opinion.

THE DESIGN OF THE SPIROMETER

Recently Bernstein and Mendel (1951) showed that a spirometer of the conventional pattern commonly used for the M.B.C. test could give records of breathing which were grossly inaccurate. The respiratory rates at which these inaccuracies occurred were determined by the mean depth of immersion of the spirometer bell in its water-jacket, while their extent was determined by the rate, volume, and wave-form of the respiratory air-flow. Because these factors are variable in human experiments, an appropriate correction factor, applicable to every estimation on any one apparatus, cannot be deduced. It was also shown that these inaccuracies were due, at least in part, to the inertia of the moving parts of the spirometer. This caused pressure changes to occur within the bell, and these, at certain respiratory rates, tended to excite resonance in the water column in the water-jacket. The respiratory rate at which resonance occurred was dependent on the length of the water column.

By altering the design it has been possible to build a spirometer which is substantially free from recording error up to a rate of 110 R.P.M. This range is considerably greater than is possible with our conventional (Knipping) spirometer, with which aspiration of water into the connecting tubes commonly occurs at respiratory rates above about 55 R.P.M.

The design considerations were as follows:

TO REDUCE THE INERTIA OF THE MOVING PARTS.—This has been achieved as follows:

Reducing the Mass of the Bell.—In order to do this the bell was made of aluminium sheet, which is very light and strong, and its proportions were altered so as to give a better ratio between contained volume and surface area. The ideal bell would have equal length and cross-sectional diameter. This ideal has been approached, though not attained, because a compromise was adopted in which the cross-sectional area was made twice as great as that of the bell of the Knipping spirometer, in order that the same recording paper could be used for either instrument with only a simple change of scale.

Reducing the Velocity and Acceleration of the Bell.—Because the cross-sectional area of the bell is larger it will not have to move as far to accommodate the respired air. Therefore, for any specified rate of air-flow the velocity of the bell is reduced, as are also the acceleration and deceleration necessary at the turn-over points at the top and bottom of the excursion of the bell.

Substituting Thin Cord for Compensated Chain Suspension.—This results in a considerable reduction in weight.

Using Two Very Light Pulleys.—These, of small diameter, carried on ball-races, are used in place of one which is large and heavy. It can be shown that the moment of inertia of a disc about its centre of revolution is proportional to the square of the radius, and this change reduces the inertia and also the frictional resistance to movement.

TO REDUCE THE TENDENCY OF THE WATER COLUMN TO RESONATE.—This was achieved as follows:

As a Consequence of the Reduced Length of the Bell.—This necessarily reduces the length of the water column, and its resonant frequency is thus raised to a value outside the range in which recordings are to be made (Bernstein and Mendel, 1951).

By Damping the Oscillatory Movements of the Water.—The pressure changes within the bell, which are due to its inertia, act only on the surface area of the water within the bell, but must move the entire mass of water in the water-jacket in order to cause oscillation. If the surface area of water inside the bell is made small, and the total mass of water large, then the pressure changes act at a great mechanical disadvantage and consequently produce minimal movements of the water. The annular radius of the water-jacket inside the bell was therefore made as small as possible compatible with avoiding contact between the bell and the inner cylinder of the water-jacket, and the outer annular radius was made as large as conveniently possible.

The differences in design between the spirometer based on these considerations and a conventional (Knipping type) spirometer are shown in Fig. 1 and Table I. A spirometer has been constructed with the dimensions shown in Table I, and this has been tested by means of a reciprocating piston pump delivering a constant output of 2,800 ml. per stroke, at rates up to 110 strokes per minute (S.P.M.). The results are shown in Fig. 2, and are compared with those given by the conventional form of spirometer in a comparable series of tests.

There can be no doubt that the new spirometer gives a much more accurate recording than the old. The error is always positive and never exceeds 10%, and the response curve is almost a straight line. At no frequency in the range tested has any aspiration of water occurred; indeed it is usually difficult to detect any movement in the water column, in contrast to the conventional type spirometer in which the movement of the water column may be as much as 5 cm. in amplitude.

TABLE I
PHYSICAL CHARACTERISTICS OF SPIROMETERS USED

	Knipping Spirometer		New Spirometer
	Original Bell	Light Aluminium Bell	
Bell:			
Material	Brass	Aluminium	Aluminium
Thickness of wall	0·45 mm.	0·30 mm.	0·30 mm.
Length	40 cm.	40 cm.	28·8 cm.
Diameter	16·9 cm.	13·5 cm.	23·1 cm.
Useable capacity	6·0 litres	4·8 litres	9·0 litres
Weight	868 g.	160 g.	250 g.
Counter-balance:			
Weight	828 g.	120 g.	200 g.
Suspension:			
Material	Metal chain	Cord	Cord
Weight	104 g.	Negligible	Negligible
Total weight of moving parts	1,800 g.	280 g.	450 g.
Pulleys:			
Number used	One	One	Two
Material	Duralumin		"Perspex"
Diameter	12·5 cm.		6·0 cm.
Thickness	1·0 cm. (approx.)		3·0 mm.
Weight	245 g.		22·5 g. (each)
Moment of inertia	4,786 g. cm.²		314 g.cm.² (Total for two pulleys)

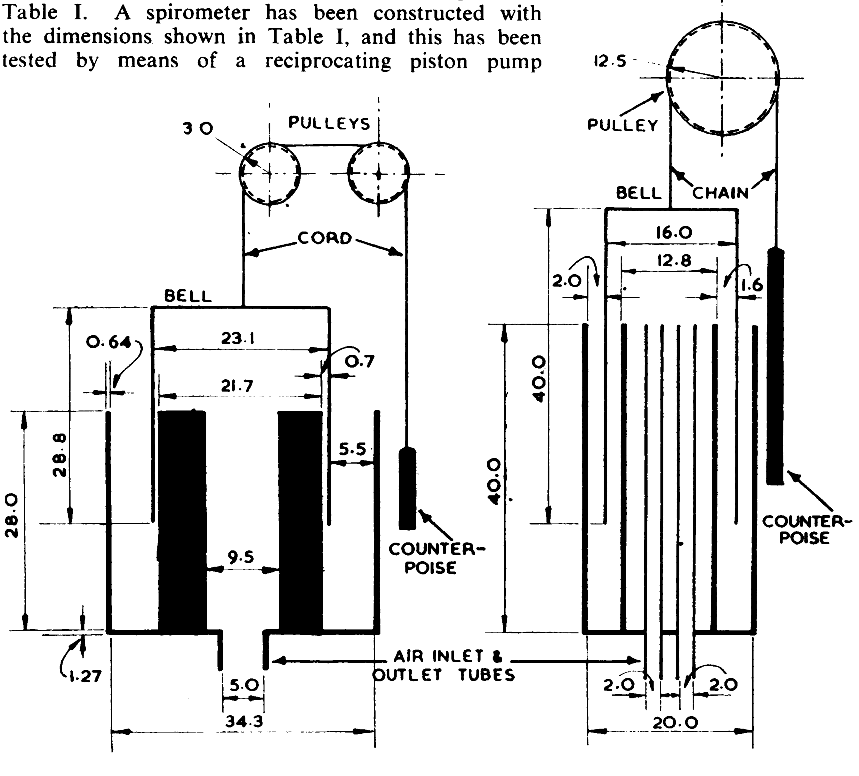

FIG. 1.—Diagram to show the dimensions of the new design of spirometer compared with those of a conventional (Knipping) spirometer. All dimensions are in cm.

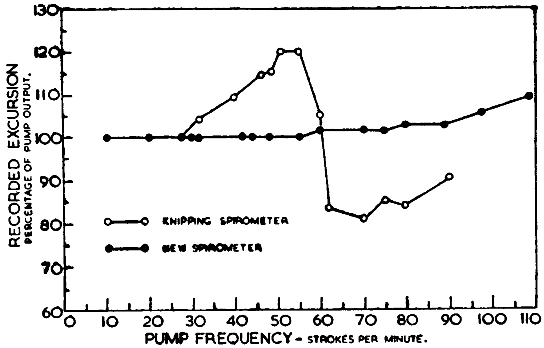

FIG. 2.—Frequency response curves of Knipping spirometer (open circles) and new spirometer (black circles) determined with a piston pump delivering 2,800 ml. per stroke.

The use of the wider bell decreases the accuracy with which measurements of volume can be made. The volume can be read in the conventional spirometer to within 20 ml. (equivalent to the thickness of the pen-marking), but when the cross-sectional area of the bell is doubled the thickness of the pen-marking represents 40 ml. This inaccuracy will lead to an error of about ±2% in the estimated M.B.C. There will also be an increase in the "dead space" of the apparatus which is an advantage when the M.B.C. is being measured, as the larger the "dead space" the smaller will be the pressure changes within the bell. Substitution of cord for the compensating chain will mean that the bell will be exactly counterpoised only in the mid position. The weight saved by omission of the chain suspension (104 g. in our spirometer) is of greater importance than the imbalance caused by the absence of the chain, which is never more than 30 g. (equivalent to a pressure of ±0.7 mm. water) in any position of the bell.

The improvements recorded above had been achieved by major modifications in the design of the spirometer. As the construction of such a spirometer is relatively expensive, an effort was made to improve the performance of the Knipping spirometer by modifying it so as to incorporate what were considered to be the most important of these principles. An aluminium bell was made of smaller diameter than the original bell. This had the effect of reducing the inner annular space and increasing the outer one. The dimensions of this bell, in comparison with the original brass bell, are given in Table I. It is apparent that the use of the aluminium bell and the replacement of the chain suspension by cord results in a considerable reduction of weight. The performance of the spirometer when fitted with this bell was tested by means of the reciprocating pump, delivering 2,800 ml. per stroke at rates from 30 to 90 S.P.M. Over this range the results were as good as those obtained with the new spirometer. This may well be a simple method of improving the performance of a spirometer for those who do not wish to incur the expense and trouble of building one of the new design.

THE RELATIONSHIP BETWEEN M.V.C. AND RESPIRATORY RATE

The M.B.C., which takes no account of respiratory rate, is defined as the greatest amount of air which can be breathed by an individual in one minute. The maximum ventilatory capacity (M.V.C.), on the other hand, is defined as the greatest amount of air which can be breathed by an individual in one minute at a specified respiratory rate. There are, therefore, many values for the M.V.C. of a subject, but only one value for his M.B.C.

In order to investigate the relationship between the rate of breathing and the M.V.C., experiments were carried out on 14 normal young adults who had been previously investigated (D'Silva and Mendel, 1950).

On the last occasion it was not possible to study fully the effect of the rate of breathing on the M.V.C. because water was aspirated from the water seal of the spirometer into the connecting tubes at rates above 55 R.P.M. Also, the results obtained at 40 and at 50 R.P.M. were not reliable because of the spirometer error described.

Using the same technique as previously described, the maximum ventilatory capacity of each of the 14 subjects was determined at six rates of breathing, namely 30, 40, 50, 60, 70, and 80 R.P.M. The rate of breathing, as measured, was always within 2 R.P.M. of the frequency set by the metronome and, for purposes of tabulation, the subject's performance was recorded as at 30, 40, etc., R.P.M.

Fig. 3 shows the mean values of the performances of the 14 subjects compared with the values

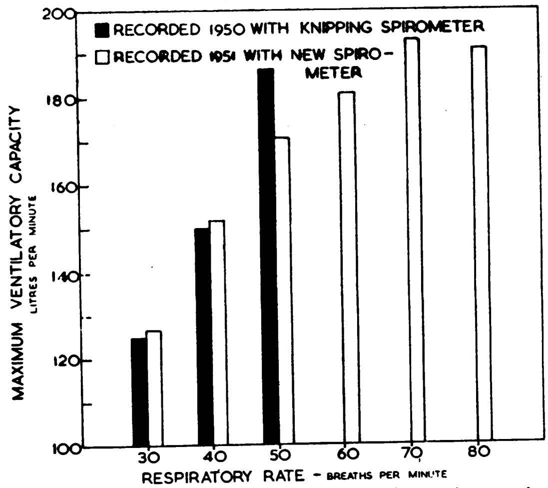

FIG. 3.—The M.V.C. (mean value for 14 subjects) at various respiratory rates, when determined on a Knipping spirometer in 1950 and on the new spirometer in 1951.

obtained a year earlier. It can be seen that the two sets of measurements at 30 and 40 R.P.M. agree remarkably well. At 50 R.P.M. the mean of the results obtained with the new spirometer was 15 litres per minute less than with the old. This difference is statistically significant ($P<0.01$). In view of the 20% positive recording error at this speed in the old spirometer (D'Silva and Mendel, 1950), this difference, though significant, was less in amount than expected.

A possible explanation is as follows. The pump used to test the accuracy of the spirometer is rigid and is empty at the end of an expiratory stroke, and therefore any pressure changes due to inertia or water column resonance could affect only the easily movable spirometer bell. The lungs, on the other hand, are elastic, of a larger volume than the pump, and, even in full expiration, still contain air. This reduces the pressure changes in the system, hence the volume changes in the spirometer are less.

To test this hypothesis measurements were made of the pressure in the spirometer bell during an experiment in which a human subject breathed his maximum tidal air at 55 R.P.M. into each spirometer in turn. This rate was chosen because it was known to be that at which a large positive error occurred in the Knipping spirometer. The pressures were recorded by means of a flexible metal bellows manometer. Similar measurements were made with the mechanical pump working at the same rate and with a stroke volume approximately equal to the tidal air of the human subject. The results are shown in Fig. 4. Because of the difficulties of recording rapidly changing pressures with any high degree of accuracy, these results are considered from a purely qualitative aspect. It can be seen that the pressure changes are less with the new spirometer than with the old, whether with the human subject or with the mechanical pump. It is also apparent that the pressure changes in the old spirometer are considerably less with the human subject than with the mechanical pump. This suggests that the inaccuracies should also be less with the human subject, and therefore agrees with the observations on the 14 subjects tested on both spirometers.

The highest value of the M.V.C. was obtained at 70 R.P.M. The mean figure of 193 litres per minute breathed at this rate is considerably higher than other mean values which have been published by investigators who used spirometers (Hermannsen, 1933; Gray and Green, 1945; Baldwin, Cournand, and Richards, 1948). Wright, Yee, Filley, and Stranahan (1949) obtained a mean value for the M.B.C. fairly close to ours. This may have been because they used the Douglas bag method with " high velocity " (low resistance) valves and not a spirometer to determine the M.B.C.

Thirteen of the 14 subjects breathed more in the test at 70 R.P.M. than at the lower respiratory rates. The mean figure obtained at 70 R.P.M. is greater than that obtained at lower rates, and the difference is statistically significant ($P<0.01$).

Nine subjects breathed more at 80 R.P.M. than they did at 70 R.P.M., but the increase was not statistically significant ($0.7>P>0.6$).

The effect on the M.V.C. of breathing at respiratory rates up to 200 R.P.M. was investigated in three subjects. The measurements made on each of the three subjects have been shown separately in Fig. 5 because their behaviour at high rates of breathing appeared to be different. It is not possible to draw firm conclusions from the rather erratic results obtained. Differences in the readings may be due to some extent to the difficulties in calculating the exact rate when very high rates of breathing are used.

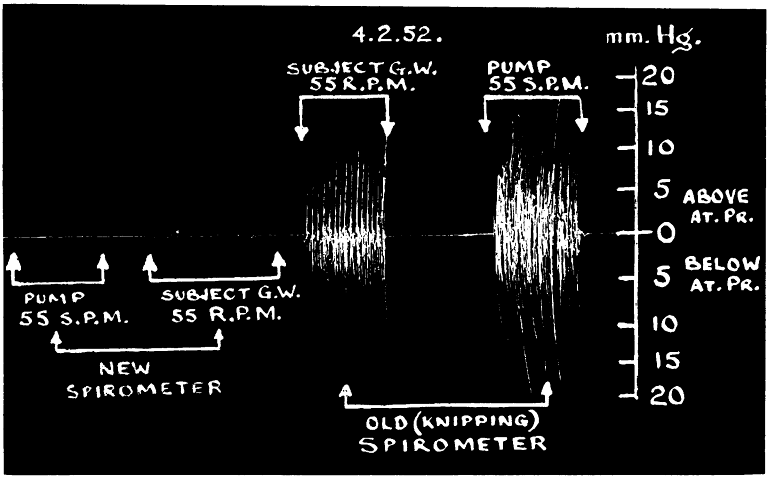

FIG 4.—Records of the pressure changes occurring in the Knipping spirometer and also in the new spirometer when recording at 55 R.P.M. from a human subject and at 55 S.P.M. from the piston pump.

From Figs. 3 and 5 it would appear that the true maximum breathing capacity of our subjects was reached at 70 R.P.M. The effect of higher rates of breathing has only been studied in three individuals, and from this small series of figures it would seem that no material increase in the volume of air breathed can be achieved at rates over 70 R.P.M.

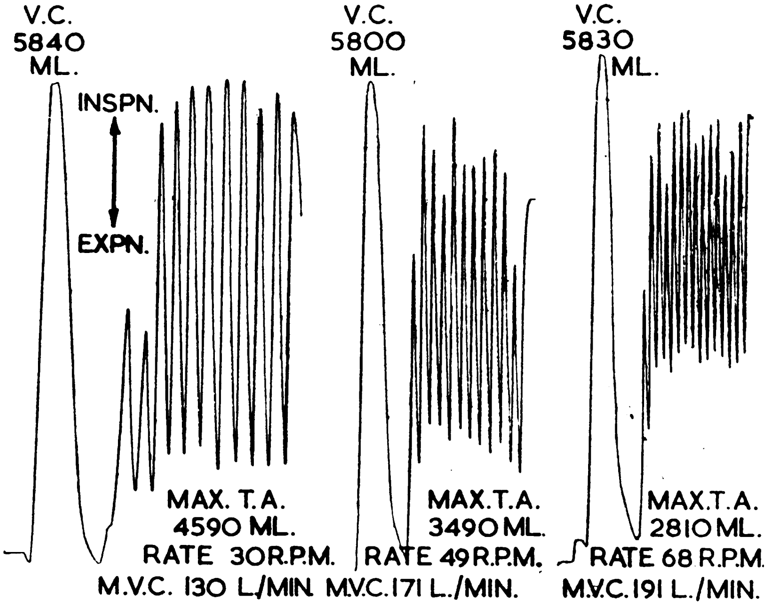

FIG. 6.—Records showing the fraction of the vital capacity used by a subject during the determination of M.V.C. at three different respiratory rates. Each record shows, at left, a fast vital capacity tracing followed, at right, by a tracing of maximum tidal air-flow at the chosen rate. The individual remains connected to the spirometer throughout the duration of each recording.

Effect of Breathing in Time to a Metronome

It has been suggested that the imposition of a respiratory pattern upon the subject impairs performance. Although our mean value for the M.V.C. at 70 R.P.M. is the highest published figure obtained in M.B.C. tests, it was felt that the effect of breathing in time to a metronome should be investigated in order to determine whether or not it impaired performance. The M.B.C. of a further six untrained subjects was recorded while they were asked to breathe "as fast and as deep as possible, the accent on speed," and they were encouraged to breathe faster and faster during the experiment. This procedure was repeated and the higher value was taken as the M.B.C. They were then instructed to breathe as deeply as possible in time with a metronome at 70 R.P.M. They were given two attempts at this type of breathing and the higher result was taken as the M.V.C. at this rate. The results are given in Table II.

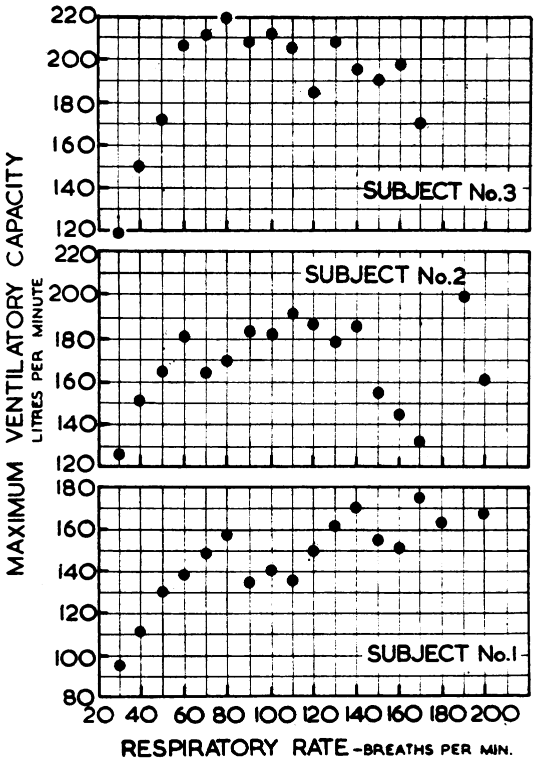

FIG. 5.—The relationship between M.V.C. and respiratory rate at rates up to 200 R.P.M. in three subjects.

TABLE II

COMPARISON OF THE MAXIMUM VENTILATORY CAPACITY OF SIX NORMAL STUDENTS BREATHING WITH AND WITHOUT A METRONOME

Subject	M.V.C. in litres/min.	
	Without Metronome at about 70 R.P.M.	With Metronome at 70 R.P.M.
1	230	220
2	186	172
3	142	138
4	154	132
5	202	196
6	207	231
Mean	187	182

It can be seen that the voluntary fast maximum breathing capacity and the M.V.C. at 70 R.P.M.

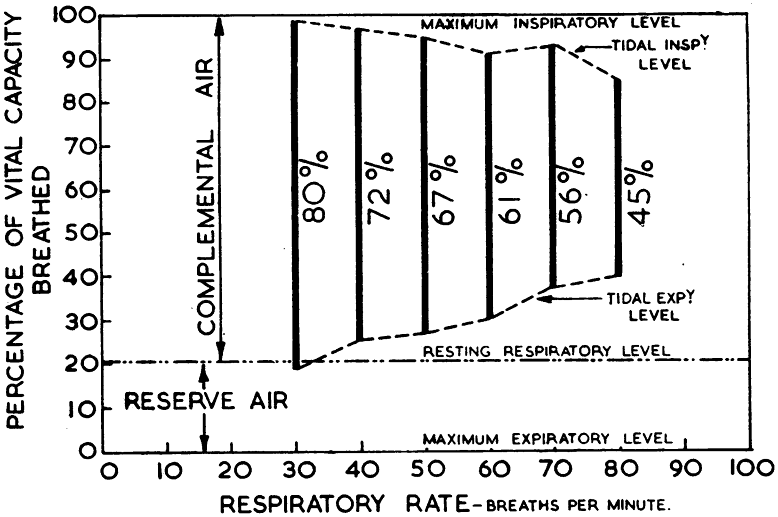

FIG. 7.—Diagram to show the average normal subdivisions of the vital capacity (Kaltreider, Fray, and Hyde, 1938) and the part of the vital capacity used (vertical black bars) when performing M.V.C. tests at various respiratory rates. The values for the percentage of vital capacity breathed and for the tidal inspiratory and expiratory levels at each rate are the mean values for eight subjects.

resulted in similar amounts of air being breathed; in the former case an average of 187 litres per minute and in the latter 182. The difference between these averages is not statistically significant (0.5>P>0.4). Breathing in time to the metronome does not appear to have limited the performance of these subjects, who achieved high values for their voluntary M.B.C. because they were encouraged to breathe faster and faster. If allowed to choose their own rate they breathed at about 40 R.P.M., and at this speed they were not able to move as much air as they could at the higher rates.

Each of the six subjects was asked which method he found more comfortable, and the reply in each case was that breathing in time to the metronome was easier because one was not in doubt as to whether to emphasize rate or depth. In addition to the 23 subjects used in these experiments, about 50 patients have been asked to breathe in time to the metronome, and all have managed to follow within ±2 R.P.M.

M.V.C. in Relation to Vital Capacity Volume

In order to determine which part of the vital capacity volume was being used in a determination of M.V.C., a tracing of vital capacity was obtained from each of eight subjects who then began maximum breathing without leaving the spirometer. Fig. 6 shows typical tracings obtained at 30, 49, and 68 R.P.M. in one subject. From Fig. 7, which represents the mean performances of the eight subjects, the part of the vital capacity volume used at various respiratory rates can be seen. As the rate of breathing increased, this group of eight normal subjects used their complementary air, and as this fraction of the vital capacity volume can be expelled more rapidly than the reserve air, as can readily be seen from a tracing of "fast vital capacity," this choice of breathing level results in the greatest amount of air being breathed during the time allowed for each complete respiration. At 70 R.P.M. the eight subjects used on the average 56% of their vital capacity at each breath.

The Effect of Rate of Breathing on the M.V.C. of Hospital Controls

In view of the finding that the M.V.C. increased up to rates of about 70 R.P.M. in normal students, it was decided to investigate whether the M.V.C. increased with increasing respiratory rate in hospital patients who were not suffering from disease of the cardio-respiratory systems. Eight outpatients were asked to breathe at 30, 40, and 50 R.P.M. and the results of these experiments are given in Table III. The values obtained at 50 R.P.M. are higher than those obtained at 30 R.P.M., and the difference is statistically significant (P<0.01).

The Effect of Rate of Breathing on the M.V.C. of Patients with Pulmonary Emphysema

Ten patients with varying degrees of pulmonary emphysema were asked to breathe at 30, 40, and 50 R.P.M. The results are to be found in Table IV. Statistically, there is no significant difference between the values obtained in these subjects at 30 and at 50 R.P.M. (0.2>P>0.1).

Discussion

Bernstein and Mendel (1951) showed that large recording errors were possible when spirometers

TABLE III

MAXIMUM VENTILATORY CAPACITY (M.V.C.) OF EIGHT HOSPITAL PATIENTS WITHOUT CARDIO-RESPIRATORY DISEASE

	Range	Mean
Age in years	22–32	26
Surface area in sq. m.	1·66–2·01	1·85
Vital capacity	3,700–5,150	4,570
M.V.C. (litres/min.) at:		
30 R.P.M.	77–110	93
40 ,,	87–130	112
50 ,,	99–141	121
Percentage of vital capacity used at:		
30 R.P.M.	54·9–75·4	68
40 ,,	46·6–65·5	59
50 ,,	40·8–65·6	53

TABLE IV

MAXIMUM VENTILATORY CAPACITY (M.V.C.) OF 10 PATIENTS WITH EMPHYSEMA

	Range	Mean
Vital capacity in ml.	1,760–3,680	2,625
M.V.C. (litres/min.) at:		
30 R.P.M.	12–56	32
40 ,,	13–73	38
50 ,,	10–74	38

of conventional type were used for measuring M.V.C. It was for this reason alone that D'Silva and Mendel (1950) recommended that a rate of 30 R.P.M. (which was known to be within the reasonably accurate range of conventional spirometers) be chosen for M.V.C. determinations. A number of previous investigators have referred briefly to a possible effect of rate of breathing on a subject's performance in the M.B.C. test, but only in a few instances have detailed observations been published. Thus Hermannsen (1933) found that a rate of breathing which resulted in a tidal air of 80% of the vital capacity gave maximum values for the M.B.C., whereas Otis and Bembower (1948) stated that there was "little gain with tidals greater than 0.3% of the vital capacity." The results from our group of medical students do not support these workers; 80% of the vital capacity was the average tidal air at 30 R.P.M., and this rate of breathing gave low values for the M.B.C. (Fig. 3). Our highest values for the M.V.C. were obtained at 70 R.P.M. Increasing the rate of breathing to 80 R.P.M. did not significantly alter the M.V.C., and though it is possible that at greater respiratory rates the M.B.C. would remain the same or might continue to rise, we have made too few observations to reach a conclusion on this point. As our highest values for the M.V.C. were obtained at 70 R.P.M., we regard this rate as the lowest at which the true M.B.C. is reached.

The results obtained by Böhme (1938), Cournand, Richards and Darling (1939), and Donald (personal communication) are supported by our observations. The discordant results referred to above may be due to apparatus errors such as we have described, or to the choice of subject. We regard our group of medical students as being not only quite physically fit but also co-operative in the highest degree. To these two factors, and an accurately recording spirometer, we attribute the consistency of our results, and performances in the test which are considerably better than the majority of those quoted in the literature. It was obvious that our group of hospital controls, who used the same apparatus, were not putting out their utmost effort. In spite of this, however, those who were regarded as having clinically normal chests gave a better performance at 50 R.P.M. than at 30. In the patients with well-marked emphysema there appeared to be no improvement at 50 R.P.M. as compared with 30.

The extent to which the results of this test of ventilatory function are dependent on the co-operation of the subject considerably detracts from its usefulness. It can still be useful, however, in indicating gross impairment of the mechanical function of the lungs, or in assessing any change which may have occurred in the patient's M.V.C. provided the observations are made at the same respiratory rate.

The prediction formula of Wright and others (1949), but not that of Baldwin and others (1948), closely represents the average M.B.C. of our group of students, but it is not possible to forecast accurately, on the basis of either formula, the M.B.C of a particular subject. The M.B.C. must depend not only on the subject's age and surface area, as the prediction formulae imply, but also on other factors. Some of these are being investigated.

SUMMARY

The design of a spirometer which records accurately at respiratory rates up to 110 R.P.M. is described.

The M.V.C. of normal individuals is related to the rate of breathing and, in a group of medical students, reached a maximum at about 70 R.P.M. Patients with emphysema did not show this dependence of M.V.C. on rates of breathing above 30 R.P.M.

We are indebted to Professor P. H. Rossier, of Zurich, who suggested the use of the aluminium bell, to the British Aluminium Company, who gave the metal, to Mr. J. Young for constructing and adjusting the apparatus, to the students who co-operated with us, and to Drs. K. Perry and N. Lloyd Rusby, who allowed us to investigate their patients.

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