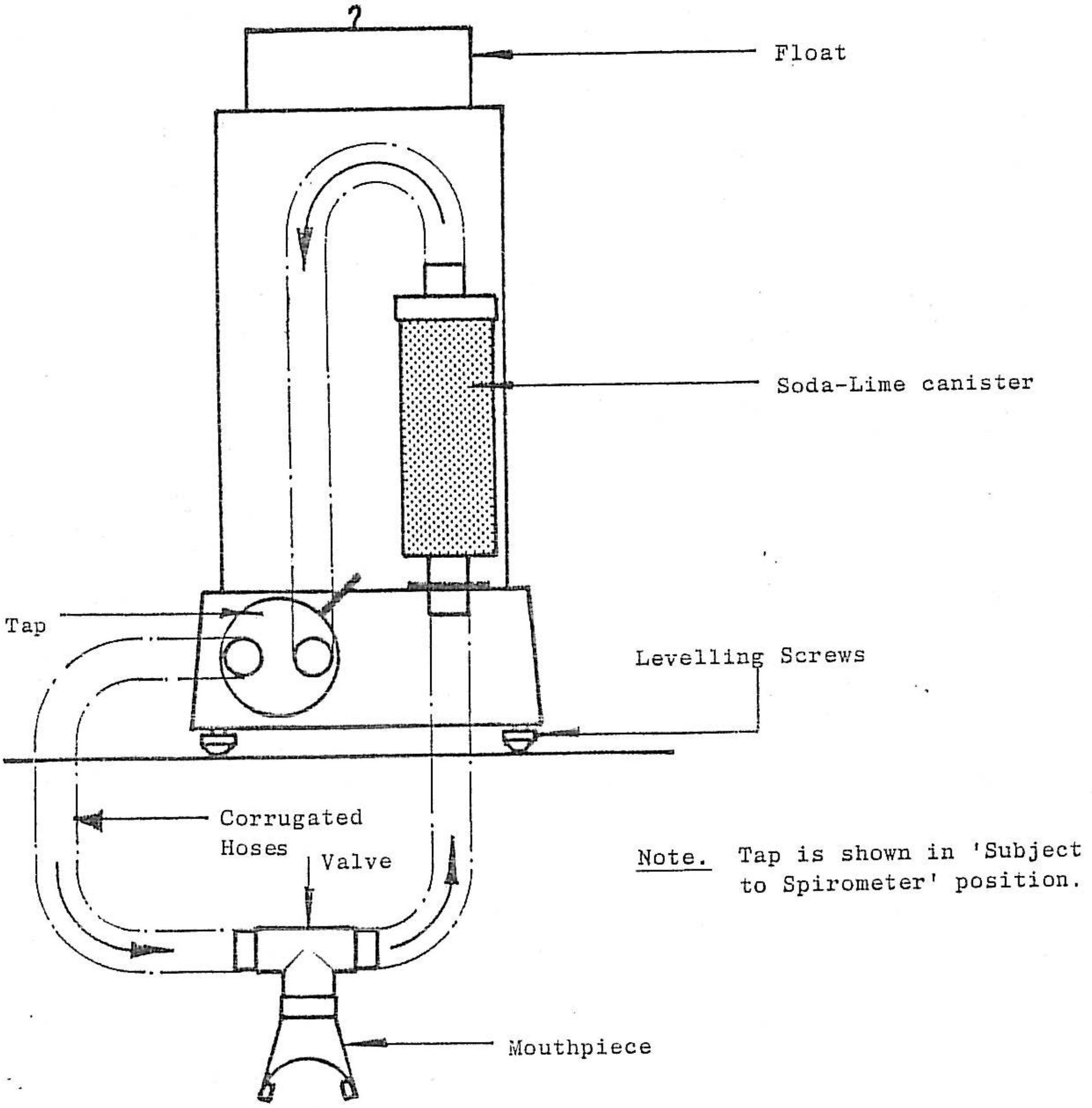
SPIROMETER, MULTI-PURPOSE MODEL,
Catalogue No. 50-1817.



Note. Tap is shown in 'Subject to Spirometer' position.

Assemble float pulley arm to the block on top edge of water tank and tighten the two thumbscrews. Pass the float cord over the pulleys and connect it to the hooks on the float and the counter-balance weight.

Assemble the external hoses with the components as shown in the diagram above. The clips on the gantry support arm are for holding the valve body, a universal joint fitting allows suitable positioning of the mouthpiece as required. Note the direction of the circuit as indicated by the arrows.

Fill the tank with water to level indicated. Adjust the levelling screw to achieve two-way level of the apparatus.

NOTES ON PRACTICAL CLASSWORK
FOR RESPIRATORY FUNCTIONS

FROM B L ANDREW

Experimental Physiology

7th ed 1965

CHAPTER THREE

RESPIRATION

3.1 Nomenclature of Respiratory Physiology

General agreement has now been reached on the subdivisions of total lung capacity. These are based on the assumption that the most stable point of the respiratory cycle is the resting end-expiratory position, i.e. during quiet respiration we tend to breathe out to the same functional residual capacity each time (Fig. 3.1). The word 'volume' has been reserved for discrete fractions of the total lung capacity; capacity is used where the measurements can be divided into smaller entities, e.g. Vital Capacity includes both Inspiratory Capacity and Expiratory Reserve Volume.

LUNG VOLUMES

VC—Vital Capacity—Maximal volume that can be expired after a maximal inspiration.

IRV—Inspiratory Reserve Volume—Maximal volume which can be inspired from end-tidal inspiration.

ERV—Expiratory Reserve Volume—Maximal volume which can be expired from the resting end-expiratory level.

IC—Inspiratory Capacity—Maximal volume which can be inspired from the resting end-expiratory level.

FRC—Functional Residual Capacity—Volume of gas in the lungs at the resting end-expiratory level.

RV—Residual Volume—Volume of gas in the lungs at the end of maximal expiration.

TLC—Total Lung Capacity—Volume of gas in the lungs at the end of a maximal inspiration.

This branch of physiology has been further systematized by the development of a shorthand notation. This consists of a list of abbreviations and a convention for their use; a list is shown in Table 3.1.

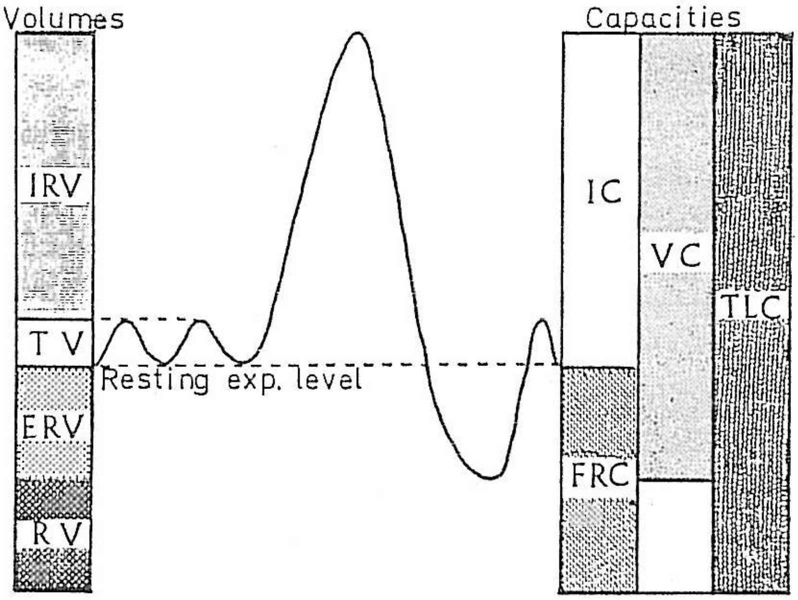

Volumes
IRV
TV
ERV
RV
Resting exp. level
Capacities
IC
VC
TLC
FRC

Fig. 3.1

SYMBOLS USED IN RESPIRATORY PHYSIOLOGY

Primary Symbols

P = pressure
V = volume
F = fractional concentration in the dry gas phase
f = respiratory frequency
Q = volume of blood
C = concentration of gas in blood phase
S = % saturation of haemoglobin with O_2

Secondary Symbols

(1) Gas Phase

I = inspired air
E = expired air
A = alveolar gas
T = tidal gas
D = dead space air
B = barometric

(2) Blood Phase

a = arterial blood
v = venous blood
c = capillary blood

TABLE 3.1

Symbols used in Respiratory Physiology based on Pappenheimer, J. *et al. Fed. Proc.*, 9, 602-605, 1950. Gandevia, B. & Hugh-Jones, P. P. *Thorax*, 12, 280-293, 1957.

The Primary Variable, denoted by the first symbol, is the parameter to be measured; it is represented by a large letter, usually a capital. It is followed by the Secondary Variable, which denotes where the primary variable was applied. This is given as a small capital for quantities in the gas phase and a lower case letter for the blood phase and these symbols are written on the same line as the primary variable. The particular gas measured is printed next, as a subscript, using the normal chemical symbol. Finally a dot above a primary symbol indicates a time derivative and a short dash indicates a mean value.

Thus,

$\dot{V}\mathrm{A}$ = Alveolar ventilation per minute
$\mathrm{Pa}_{\mathrm{CO}_2}$ = Partial pressure of CO_2 in arterial blood
$\mathrm{FI}_{\mathrm{O}_2}$ = Fractional concentration of O_2 in inspired gas
PB = Barometric Pressure
$\overline{\mathrm{P}}\mathrm{B}$ = Mean Barometric Pressure

3.2 Spirometry

Many measurements of lung volumes and ventilation are obtained with the use of a spirometer. This is simply a counterpoised gasholder. A writing-point fixed to the counterweight is made to write on a variable-speed kymograph drum. The ideal spirometer offers so little resistance to the movement of air to and from the subject's lungs that its presence is imperceptible and the subject's respiratory movements are unaffected by the apparatus. This ideal is difficult to achieve but it is approached by the use of wide-bore airways, light-weight gas bells, and low-inertia recording devices. Soda-lime absorbers and one-way valves introduce airway resistance and are best dispensed with if possible. They are necessary, of course, where the spirometer is used to measure oxygen consumption by the closed circuit method (para. 4.2) and here some lack of fidelity in the record can be tolerated. Some improvement is obtained by using a pump to circulate the gas through the carbon dioxide absorbent. The effects of airway resistance are well illustrated by Campbell *et al.* (1961). *Clin. Sci.* **21**, 311.

It is possible to avoid the use of a soda-lime absorber in two ways. Firstly, use the spirometer only to collect and measure the expired air, as in para. 3.6 or in FEV tests, or secondly, limit the duration of rebreathing from a large capacity spirometer so that carbon dioxide accumulation is unimportant. When measuring MVV as in para. 3.10 an accumulation of carbon dioxide is actually helpful.

For tests of short duration, air is used to fill the spirometer. Pure oxygen depresses ventilation even in the normal subject and in abnormal conditions where there has been some persistent anoxic drive it may produce marked depression. In longer lasting tests where oxygen consumption is being studied rather than respiratory rhythm and minute ventilation, pure oxygen is used to fill the spirometer.

Some further points of spirometric technique must also be considered. Consecutive determinations of any lung volume must be made with the subject in the same position. The effect of posture is illustrated by its effect on resting end-expiratory position in para. 3.5. Before starting a recording, the bell should be raised and lowered with the ink-writer against the record paper. This provides a vertical axis to assist measurements on the paper. Make sure the spirometer is level and that the bell does not touch the sides.

Note that gas cylinders are provided with two valves, a main cock attached to the cylinder itself and a secondary valve which is screwed into the cylinder orifice. The main cock is used to seal the cylinder when it is not in use. The secondary valve may automatically regulate the output pressure to a few pounds per sq. in. giving variable volume flow at constant pressure or it may be a simple needle valve which must be adjusted manually to give the correct output pressure, and volume flow depends on the pressure selected.

Several types of mask or mouthpiece are used to connect the subject to the spirometer. Short-lasting tests which involve high airflow rates such as FEV are best performed with a mask pressed against the face to include mouth and nose. In other tests where a small leak will cause great errors as in closed-circuit oxygen consumption measurements, a rubber flanged tube is fitted between the lips and teeth and gripped by the subject. For many tests a 3 cm diameter glass tube gripped by the lips is suitable.

3·3 Gas Laws: Volume Conversions

The respiratory gases obey the fundamental physical laws governing the behaviour of gases. The most important of these are:

1. *Boyle's Law*: The volume occupied by a quantity of gas is inversely proportional to its absolute pressure, if its temperature remains constant.

i.e. $P_1V_1 = P_2V_2$, where $T_1 = T_2$

2. *Charles' Law*: The volume occupied by a quantity of gas is directly proportional to its absolute temperature, if the pressure of the gas remains constant.

i.e. $V_1/T_1 = V_2/T_2$, where $P_1 = P_2$

1 and 2 can be combined, $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$

Absolute temperature is recorded in the Kelvin scale (°K). Zero on the scale is equivalent to $-273°$ C and is the temperature at which any body would be incapable of releasing further thermal energy. Absolute pressure is the actual pressure at a point in a fluid (gas or liquid).

3. *Dalton's Law of Partial Pressures*: If several gases are placed in the same container, the total pressure exerted is the sum of the partial pressures which each gas would exert if it alone occupied the container.

i.e. $P_{\text{Total}} = P_1 + P_2 + P_3 \ldots + P_n$

Alternatively, if n_A moles of gas A were alone in a volume V at temperature T, the pressure would be

$P_A = n_A . RT/V$ (where R = volume occupied by 1 mole of any gas at 0° C and 1 Atmos. pressure)

and similarly $P_B = n_B . RT/V$

$\therefore P_A/P_B = n_A/n_B$

e.g. In dry air, 78·09 per cent. of the molecules are N_2

$\therefore P_{N_2}/P_{Total} = 78{\cdot}09/100$

∴ Partial pressure of N_2 at a pressure of 760 mm Hg

$$= \frac{760 \times 78{\cdot}09}{100}$$

$$= 593{\cdot}5 \text{ mm Hg.}$$

4. At a gas/liquid interface created by exposing a liquid to a vacuum, the number of molecules with sufficient kinetic energy to evaporate (per second per unit area of liquid surface) is proportional to the temperature of the liquid. The number of molecules which return from the gaseous to the liquid phase is that number which strike unit area of the surface in one second, and at a given temperature this is proportional to the vapour pressure.

Since rate of evaporation = rate of condensation at equilibrium, it follows that the vapour pressure is determined by the temperature.

Where an interface exists between a liquid and a permanent gas (or gases) e.g. air, such an equilibrium state is reached. Then, by Dalton's law,

P_{Total} = Partial pressure exerted by each gas + partial pressure exerted by the fluid in the gaseous phase.

In physiological practice, this means the pressure exerted by water vapour. Air is saturated with water vapour when the partial pressure exerted by the vapour is maximal for a given temperature.

5. *Solubility of Gases in Liquids: Henry's Law*

The quantity of gas physically dissolved in a liquid at constant temperature is directly proportional to the partial pressure of the gas in the gas phase. The solubility coefficient for a gas in a particular liquid is the amount of the gas which will dissolve in unit volume of liquid per unit rise in partial pressure, e.g. the solubility coefficient of CO_2 in water is 0·0334, i.e. if P = partial pressure of CO_2 in mm Hg, 0·0334P m-moles of CO_2 will dissolve per kg. of H_2O at 37° C.

The partial pressure of a gas in a liquid is called its tension and is not measured directly but is obtained by measuring the partial pressure of the gas in an equilibrated gas phase. Note, too, that the partial pressure of a gas in a liquid is related only to the amount in physical solution; the content of gas in a liquid may be considerably higher, e.g. CO_2 in blood, if gas is also held in chemical solution. Such chemically combined gas does not contribute to the partial pressure.

Applying these concepts, respiratory volumes can be specified in terms of the pressure, temperature and water vapour saturation and any two volumes can be equated by reducing them to similar conditions with respect to these variables. Thus volumes may be expressed as:

(1) Ambient Temperature and Pressure, Saturated with water vapour—ATPS, e.g. the volume change in a spirometer (para. 3.2).

(2) Body Temperature and Pressure, Saturated with water vapour—BTPS, e.g. the volume of one of the subdivisions of lung.

(3) Standard Temperature and Pressure, Dry—STPD. This can be used as a reference scale to which (1) and (2) are converted to facilitate equation of volumes. Standard (previously Normal) Temperature is 273° K (0° C) and Standard Pressure is 760 mm Hg.

The principal conversions used are:

(1) ATPS to BTPS

$$V_{BTPS} = V_{ATPS} \times \frac{P_B - P_{H_2O}}{P_B - 47} \times \frac{310}{273 + t^\circ\,C}$$

Since small deviations from standard barometric pressure produce little change in the final result, this can be simplified to a correction for temperature only and Table 3.2 gives a list of conversion factors for the normal range of temperatures encountered.

CONVERSION FACTORS

Factor to convert Volume to 37° C Sat.	When gas temp. in ° C Sat. is
1·102	20
1·096	21
1·091	22
1·085	23
1·080	24
1·075	25
1·068	26
1·063	27
1·057	28
1·051	29
1·045	30
1·039	31
1·032	32
1·026	33
1·020	34
1·014	35
1·007	36
1·000	37

TABLE 3.2

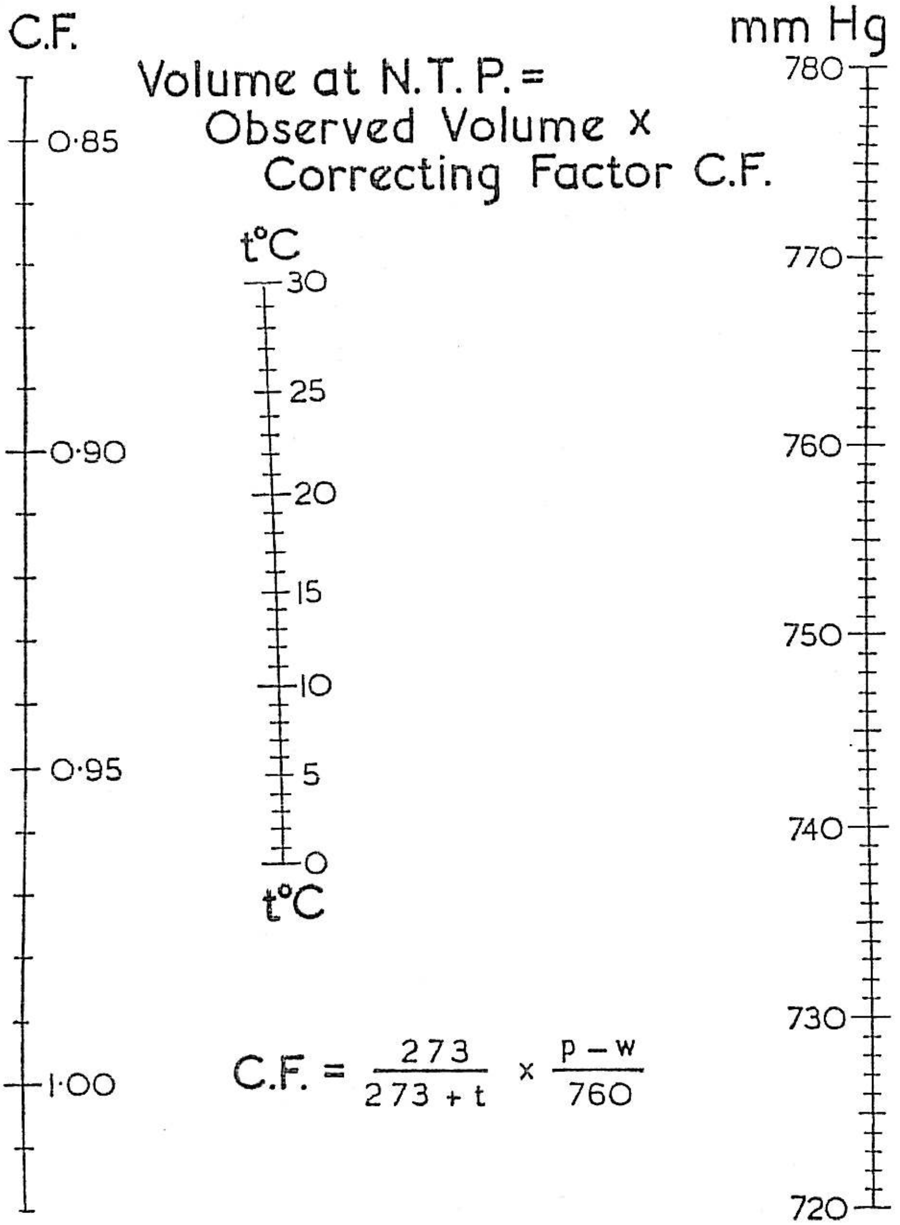


FIG. 3.2

Nomogram for obtaining the correcting factor C.F. by which the volume of a gas at any pressure between 720 and 780 mm Hg and saturated with water vapour at any temperature between 0° and 30° C can be reduced to N.T.P. (Weir, J. B. de V. (1949). *J. Physiol.*, 109, 1).

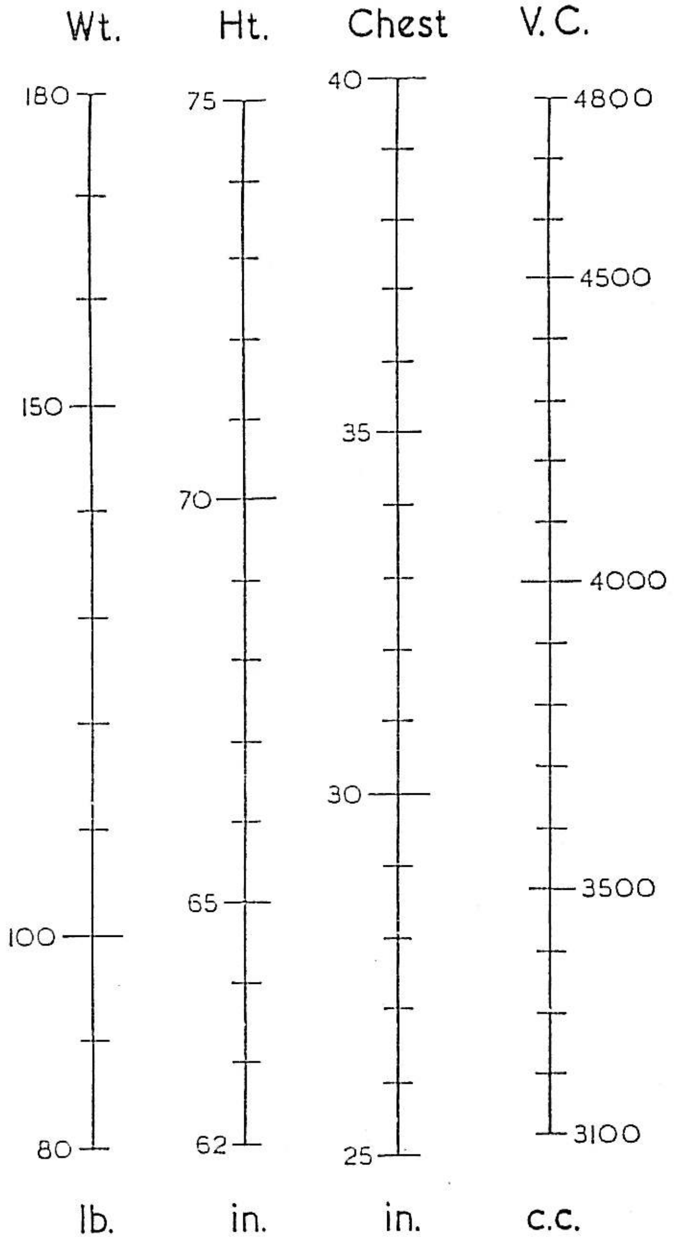

Wt.
Ht.
Chest
V. C.
180
150
100
80
75
70
65
62
40
35
30
25
4800
4500
4000
3500
3100
lb.
in.
in.
c.c.

Fig. 3.3

in the standing position the subject carefully resumes the supine position on the couch. Mark the record at the appropriate points and discuss your results.

3.6 Tidal Volume

This is the volume of air passing into or out of the lungs at each respiration. It is notoriously difficult to measure the normal resting tidal volume accurately because, apart from the considerations of para. 3.2, as soon as someone thinks of his breathing pattern (an inevitable accompaniment of use of nose-clip, mouthpiece and spirometer) he tends to hyperventilate. This effect can be minimized by repeating the experimental procedure several times.

Fit the subject with a nose-clip and a rubber mouthpiece connected to a directional valve of the type illustrated in Figure 3.4. He is allowed to inspire from the atmosphere and the expiratory end is connected to a spirometer. Alternatively, use a short wide glass tube as a mouthpiece and allow the subject to rebreathe from a large capacity air-filled spirometer. In each case, use a low-resistance recording spirometer without a CO_2 absorber. Instruct the subject to breathe quietly and record several breaths. Take several records and, if the rebreathing method is used flush out the spirometer between each. Continue till consistent records are obtained. Take the average of several breaths and express the resting tidal volume in litres. Count the respiratory rate.

Multiply the tidal volume by the number of breaths per minute. This gives the ventilation for one minute, normally called the Minute Volume (para. 3.9).

3.7 Vital Capacity

1. Sterilize and rinse a mouthpiece, and fit it to the tubing of a spirometer. See that the bell is at its lowest position i.e. the spirometer is empty. Expire and inspire as fully as possible from the atmosphere, then while holding the nose, expire as deeply as possible, but without undue haste, into the spirometer. The volume measured in this way is the Vital Capacity.

2. It is useful to measure the vital capacity in another way, along with the other lung volumes, so that their inter-relationship is better appreciated. The bell is filled with room air and positioned so that the pen is recording in the middle part of the paper. Set the drum speed at approximately 30 mm per second. The subject inserts the mouthpiece having first put on a nose-clip. He is instructed to breathe normally eight or nine times into the spirometer and then inhale until the maximal inspiratory position is recorded. Then he exhales smoothly and completely until exhalation is complete, and he finishes with a few normal respirations. The spirometer is emptied and refilled with room air. The subject again breathes normally to and from the bell for several breaths, takes a maximal inspiration but then returns to normal breathing for a few breaths after which he breathes out maximally.

From these records the TV, IRV, ERV, IC and VC can be measured. In addition, if the ERV and the IC from the second recording are added, they should equal the value obtained for the VC in the first test. When a carefully performed two-stage VC

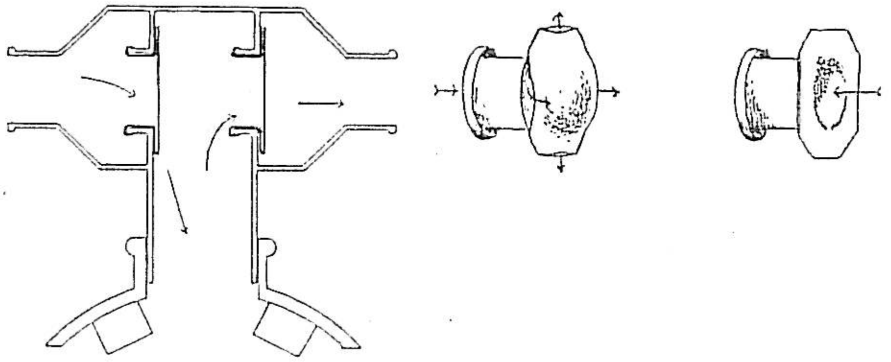


FIG. 3.4
The diagram on the left shows the mouthpiece and valve housing and the path of the air to the spirometer which is connected by a wide bore rubber pipe to the right-hand tube of the housing. The two small sketches on the right indicate how the rubber valves behave according to the direction of the air stream. In other types of apparatus the valves may consist simply of thin flexible rubber discs lying over perforated metal discs.

gives values substantially greater than those obtained with the single breath method, the subject is probably suffering from obstructive airway disease.

3.8 Residual Volume, Functional Residual Capacity and Total Lung Capacity

As the residual volume is that volume remaining in the lungs after a maximal exhalation, it is evident that it cannot be determined by direct spirometry. In addition, since the residual volume forms a part of both the Functional Residual Capacity and the Total Lung Capacity, these volumes too must be determined by indirect means.

1. *Open method*: This is based on the fact that when air is breathed, gas in the lungs is 80 per cent. nitrogen. If the amount of nitrogen in the lungs at a specific position of the breathing cycle could be determined, then the total volume of gas in the lungs at that time could be calculated. All the nitrogen can be flushed out of the lungs by breathing N_2-free oxygen and collecting the expired air in a Douglas bag. The total volume of expired air and its nitrogen concentration are measured and so the total volume of nitrogen coming from the lungs is calculated.

The lung volume measured depends on the point at which the test is started. If collection is started precisely at the end of a complete inspiration, then the total lung capacity is the volume measured. If it is begun at full expiration, residual volume is measured. If the resting expiratory level is taken as the starting point, the volume determined is the functional residual capacity. As the end of a normal expiration is a more constant point than either full inspiration or full expiration, it is most usual to measure the functional residual capacity.

Procedure: Two Douglas bags are required. Fit a large bore 2-way tap to each bag and then connect one tap to the inlet and one to the outlet of a 3-way valve and mouthpiece by corrugated rubber piping. Connect the oxygen cylinder to the side tube of the bag which is attached to the inlet of the mouthpiece. Flush out the whole system several times so that it is nitrogen-free. Close the tap on the inlet bag and fill the bag with oxygen. Make sure that the side tubes of both bags are closed. The subject then adjusts the nose-clip and inserts the mouthpiece. The tap of the mouthpiece is open to the atmosphere and the subject breathes to and from the atmosphere until his respiration has settled. At the end of a normal expiration, the mouthpiece is closed and both large taps on the Douglas bag are opened so that the subject inspires from the oxygen-filled bag and expires into the collecting bag. The subject should continue to breathe through the apparatus for seven minutes; the large tap on the collecting bag is then closed.

Introduce a sample of expired air from the bag into a gas analyser through the narrow side tube. After analysis of the sample the large tube of the Douglas bag is attached to a gas meter, and using gentle pressure on the bag, the volume of the expired air is measured. The volume of the expired air used in analysis may be neglected as it should be quite small.

Sample calculation:

Volume of expired air = 40 litres

Conc. of N_2 in expired air = 5 per cent.

Amount of N_2 in lungs (at resting exp. level) $= \left(\frac{5}{100} \times 40\right) = 2$ litres

But conc. of N_2 in lungs = 80 per cent.

Functional residual capacity $= \left(2 \times \frac{100}{80}\right) = 2{\cdot}5$ litres

2. *Closed Method*: With this method we make use of a closed circuit and a gas not normally present in the lungs. This method depends on the fact that we start with a known volume (the spirometer)$_1$ containing a known concentration of Helium, and an unknown volume (FRC) containing a known concentration of Helium (0 per cent.). After rebreathing for a short time in this closed system, the gases come into equilibrium. The new concentration of helium in the system is then measured. As theoretically no helium is lost from the system during rebreathing, the amount of helium in the lungs and in the spirometer at the beginning of the test is the same as the amount in the lungs and the spirometer at the end of the test.

Procedure: 1. Empty the spirometer, leave the mouthpiece valve in the open position, and insert a rubber bung into the valve opening. Inscribe a short zero line and admit about 800 ml. of helium$_{17}$. Draw a helium line by turning the drum through about 10 minutes of the calibrated paper.

2. Return the drum to the starting point and admit about 1·75 litres of O_2.

3. Turn the blower on to mix the gases for 10 minutes.

4. Switch on the Helium Meter indicator,$_{25}$ turn the switch on the front of the instrument to the 'TEST' position and use the control 'RHEO' to bring the pointer to the red TEST mark. Turn the switch to 'HELIUM IN AIR'.

5. Turn the mouthpiece valve to the closed position and remove the rubber bung. Attach the mouthpiece.

6. Put on nose-clip and insert mouthpiece. Subject should be seated in a comfortable position.

7. Have the subject breathe room air until his respirations are quiet and stable. Start the drum and at the end of a normal expiration, quickly turn the valve connecting the subject to the circuit.

8. When the respiratory base line crosses the helium line read the concentration on the helium meter, first checking that the test reading is still on the red test mark when the switch is turned to the 'TEST' position. Then disconnect the subject from the system.

Calculation:

$$\text{FRC} = \frac{\text{Helium added}}{\text{Final helium conc.}} - (\text{He added} + \text{dead space})$$

The dead space is given with each instrument. When great accuracy is required a correction factor should be included to allow for the small amount of helium lost into the circulation and for the increment in the circuit of nitrogen from the subject.

Enter in Table 3.4 your values of the subdivisions of the lung volume. All values should be corrected to B.T.P.S. (body temperature and pressure, saturated).

Total lung capacity	Vital capacity	Inspiratory capacity	Inspiratory reserve volume
			Tidal volume
		Functional residual capacity	Expiratory reserve volume
	Residual volume		Residual volume

TABLE 3.4

3.9 Pulmonary Ventilation

If pulmonary ventilation is to be measured when the subject is moving about, then use of a spirometer is no longer possible. A simple method is to collect the expired air in a Douglas bag over a timed interval and measure the volume collected by emptying the bag through a gas meter.

The bag is mounted on the subject's back, a nose-clip is applied, and by means of a mouthpiece with non-return valves the expired air is collected in the Douglas bag (Fig. 3.4).

Collect expired air over a suitable time interval (a) with subject at rest; (b) while walking briskly about the laboratory; (c) while climbing the stairs.

Express result as litres of air per minute.

3.10 Maximum Voluntary Ventilation (MVV)

This measure was formerly called the Maximum Breathing Capacity, and it is that volume of gas which can be breathed by maximum voluntary effort in one minute. In this test, the subject breathes as deeply and as rapidly as he can through a low-resistance system for 15 seconds. He is permitted to choose his own frequency and tidal volume, but in fit young people the respiratory rate should be at least 70 per minute. The maximum voluntary ventilation is a strenuous test and will give an index of the maximum breathing capacity only if the subject is fully co-operative.

1. Set up a spirometer of the low-resistance, Bernstein type, and set the recording drum at a fairly fast speed. Add air to the spirometer until the pen is recording in the mid-portion of the paper. A soda-lime canister is not used as this adds to the resistance and a slight build-up of CO_2 is advantageous. The subject adjusts the mouthpiece and nose-clip, and the mouthpiece tap is turned to allow the subject to breathe in and out of the bell. Start the recording drum and record one or two normal respirations. The subject then breathes as deeply and as rapidly as he can for 15 seconds. Switch off the motor and remove the paper. Horizontal lines are drawn which will pass through most of the inspiratory and expiratory peaks. The distance between these lines represents the average volume and this is multiplied by the number of breaths in the 15 second period. This result is in turn multiplied by 4/1000 so that the answer is expressed in litres/minute.

2. The subject takes a maximal inspiration, fits a nose-clip and then breathes as rapidly and as deeply as possible for 15 seconds into a rebreathing bag mounted within an integrating plethysmograph. In this apparatus a volume of air equal to each breath is passed through a gas meter and the pulmonary ventilation is read directly from a dial calibrated in litres.

Compare your own maximum voluntary ventilation with the ventilation achieved during fast stair-climbing and with your minute volume at rest.

The MVV is usually found to be 20 times the minute volume at rest and this relationship gives some idea of pulmonary reserve.

3.11 Forced Inspiratory and Expiratory Spirograms

Many feeble and ill subjects are unable to perform as strenuous a test as the MVV, and so there has been a tendency to replace it with the recording of a single forced inspiration, or, more commonly, a single forced expiration. Many methods of recording and measuring these spirograms have been proposed; the most commonly used measurements can be obtained with the following technique.

Empty the air from the bell of a low resistance spirometer and set the kymograph to a fast speed. Wearing a nose-clip, the subject takes as deep a breath as possible from the atmosphere, inserts the mouthpiece and blows as hard as possible into the spirometer. At the end of expiration, the subject breathes in, as fast and as fully as possible, from the spirometer. Stop the drum and remove the mouthpiece.

Note the slowing which occurs at the end of exhalation. On inspiration, the rate is maintained until the lungs are full.

(2) ATPS to STPD

$$V_{STPD} = V_{ATPS} \times \frac{P_B - P_{H_2O}}{760} \times \frac{273}{(273 + t^\circ C)}$$

The nomogram, Figure 3·2, gives a correcting factor over the normal ranges of pressure and temperature employed.

3·4 'Normal' Ranges: Prediction Formulae and Nomograms

Most ventilatory measurements are made quite easily but a recurring problem is the decision as to whether the values obtained for a particular subject lie within the limits of normality. To facilitate such decisions, formulae have been derived to express correlations between particular respiratory quantities and factors such as sex, height, weight or chest size. Examples of such prediction formulae are given in Table 3·3.

TABLE 3·3

PREDICTION FORMULAE

Males: VC litres = ·052 Height cm − ·022 Age − 3·60
FEV_1 litres = ·037 Height cm − 0·28 Age − 1·59
MVV l./min = 1·34 Height cm − 1·26 Age − 21·4
PFR l./min = [3·95 − (·015 Age)] × Height cm

Females: VC litres = ·041 Height cm − ·018 Age − 2·68
FEV_1 litres = ·028 Height cm − ·021 Age − ·86
MVV l./min = (71·3 − ·47 Age) × Surface Area m^2
PFR l./min = [2·93 − (·007 Age)] × Height cm

Determine your height without shoes and weight without clothes (clothed weight less 10 lb. for males and 6 lb. for females). Substitute these values in the appropriate prediction formulae and estimate the values you hope to record in later experiments.

Similar information can also be displayed in semi-graphical form i.e. as a nomogram. Figure 3·3, for example, gives an estimate of the minimum VC which could be accepted as 'normal' for a male subject aged between 18 and 30 years.

To use this nomogram, measure the chest circumference midway between inspiration and expiration with the arms at the side, passing the tape just below the angles of the scapulae and half an inch below the nipples. Plot this value and the values for height and weight already obtained on the appropriate lines. Draw a horizontal line through the lowest point, cutting the vital capacity line at right-angles. The value at the intersection is the minimum 'normal' VC.

3·5 The Effect of Posture on Functional Residual Capacity

Set up the Benedict-Roth closed circuit spirometer as described in para. 4·2. Record for four minutes with the subject lying supine on the couch, then instruct the subject, still with his mouthpiece in position, to stand up gently with as little disturbance as possible to the spirometer and airlines. The record at this point should show a rise due to the increase in functional residual volume brought about by the descent of the abdominal contents and diaphragm under the influence of gravity. After a few minutes

One measure frequently made on the expiratory curve is the timed forced expiratory volume, e.g. FEV_1—which represents the volume of gas expired in one second from the starting time. The FEV_1 will obviously be reduced in subjects with increased airway resistance. The amount of air expired from full inspiration to full expiration is of course the Vital Capacity, in this instance as it is done as quickly as possible it is called the Forced Vital Capacity—FVC. In a normal person the FEV_1 should be at least 70 per cent. of the FVC. If a person has restrictive pulmonary disease the FEV_1 and the FVC will both be less than the predicted values, but the FEV per cent. will be normal. In a person with increased airway resistance the FEV_1 and the FEV per cent. will be less than normal but the FVC may be normal.

Many workers have multiplied the FEV_1 by various factors in order to obtain an estimate of the MVV—the so-called Indirect MVV. Most investigators now prefer to use both tests or to rely solely on the measurement of a single forced expiration.

Because the starting point of the FEV_1 may be doubtful, some authorities now use the Forced Mid-expiratory Flow as a measure of the efficiency of ventilation. This is the average rate of gas flow during the middle half-volume of the FES (i.e. from 25 to 75 per cent. of the expired volume).

3.12 Peak Flow Rate

Although spirometer tests have the advantage that a permanent record is obtained, their big disadvantage is that the apparatus is not very portable. A simple and portable device, the Wright Peak Flow $Meter_{20}$, is very useful in mass surveys of lung function and as a screening test in suspected obstructive airway disease.

This device makes use of a single forced expiration but differs from most other tests of this kind in that instead of measuring the volume expired in a given time, it measures the maximum flow rate or 'peak flow'.

The subject takes a deep breath, puts the mouthpiece into his mouth and blows hard. A short sharp blast with some 'follow through' is required, but the lungs need not be emptied as in the FVC test. Return the pointer to zero after use by depressing the button beside the mouthpiece.

Take five readings and record the mean of the three highest readings.

3.13 Gas Distribution

Even in normal persons all parts of the lung are not uniformly ventilated. In certain lung diseases the ventilation may be very uneven.

Set up the apparatus as in experiment 3.8(1) but replace the Douglas bag used for collecting expired air with a 4-litre bag. Flush out the whole system carefully with oxygen several times. Fill the bag attached to the inlet with oxygen and check that the other bag is empty. (The application of suction until the bag collapses is the best method of ensuring that it is empty). Both large taps are in the closed position. When the subject is seated and mouthpiece and nose-clip adjusted, open the tap on the oxygen bag. The subject then inspires oxygen and expires into the atmosphere for seven minutes. At the end of this time a maximum inspiration is taken, the tap to the collecting bag is opened, the subject expires maximally into the bag and the tap is then closed.

Introduce a sample of the expired air into a gas-analyser and estimate the nitrogen content of the sample. This value is normally less than 2·5 per cent. In emphysema values as high as 10 per cent. are obtained because the nitrogen in the less well ventilated alveoli has not been washed out.

MECHANICS OF BREATHING

In order that the lung volume should increase during inspiration, force has to be applied to the chest by the respiratory muscles. The volume increase depends not only on the force supplied by the respiratory muscles but also on the mechanical properties of the lungs and thorax. The resistance offered by the lungs and thorax to the muscles is due to:

1. Elastic resistance.
2. Frictional resistance to deformation of tissues.
3. Resistance in airways to flow of air.
4. Inertial resistance (small and disregarded).

3.14 Lung Compliance

The elastic resistance of the lungs can be measured if we know the pressure applied to the lungs to make them increase to a known volume. Both the pressure change and the volume change are measured under 'static' conditions i.e. with no air movement occurring. If pressure and volume are measured during breathing, then the pressure change at a given volume will be greater than under static conditions because some of the pressure is needed to overcome non-elastic resistance. However, during breathing in normal persons there are two points when there is no air movement, namely at the end of inspiration and at the end of expiration. So we can make use of these two points in measuring lung elasticity. This relationship of volume to pressure is usually expressed as a volume change in litres per cm of water pressure change. This is called 'compliance' and is a measure of the stiffness of the lungs.

Method. Volume changes are measured by a spirometer fitted with a potentiometer circuit giving an electrical output of volume changes. This is fed into the 'Y' axis of an oscilloscope. As intra-pleural pressure cannot be recorded routinely, we make use of the pressure difference between the oesophagus and the mouth to give us the pressure being applied to the lungs. This is measured by means of a gas-filled latex balloon in the oesophagus and a capacitance manometer$_{26}$, the electrical output of which is led to the 'X' axis of the oscilloscope. The subject applies a nose-clip and then breathes quietly to and from the spirometer. The simultaneously recorded volume and pressure give the pressure-volume loop as seen in Figure 3.5. If points A and B are joined, the slope of AB gives us the compliance. If the angle α is acute then the lungs are stiff; if the angle is large then the lungs are compliant. The work done on the lungs to overcome elastic resistance during inspiration is given by the area ABC. The area AIB

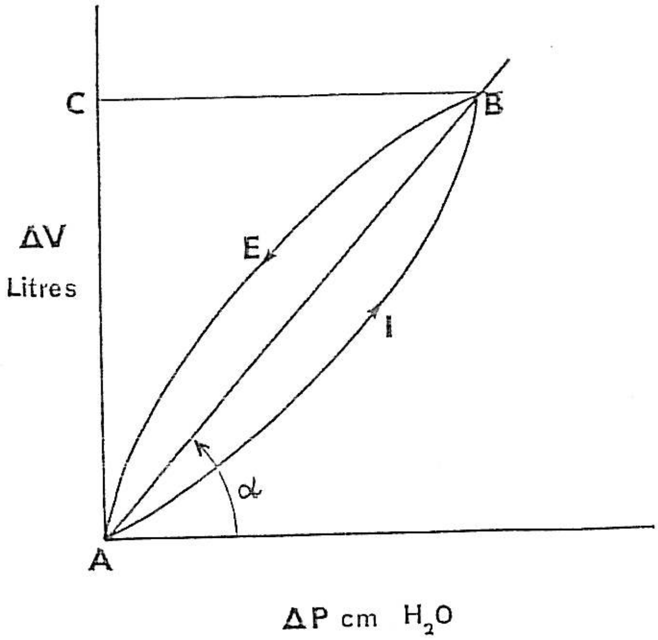


FIG. 3.5

gives the work done during inspiration to overcome the non-elastic resistance offered by the lungs. The area AIBC thus gives us the total work done on the lungs during inspiration. The energy stored in the stretched lungs is in part used to perform the work against non-elastic resistance during expiration, given by the area ABE. Widening of the pressure-volume loop is seen in any subject who has an increased airway resistance, for example, a person who suffers from the bronchiolar constriction of asthma and the extent to which the loop has been broadened can give some indication of the severity of the disease.

3·15 Combined Compliance of Chest and Lungs

Apparatus: A calibrated spirometer and mouthpiece without either valves or soda-lime absorber is used. A wide bore tap is inserted between the mouthpiece and the spirometer and a side tube to a water manometer or pressure gauge leads off from the airway between the tap and the mouthpiece. The subject wears a nose-clip.

Procedure: Draw air into the spirometer and note the reading on the scale. Starting from his normal end-expiratory position the subject now inhales air from the spirometer till his lungs are quite full, i.e. he takes in his inspiratory capacity. This volume is read from the spirometer. The tap is closed, the subject relaxes his respiratory muscles completely with open glottis. The elastic recoil pressure is read from the manometer. Repeat the procedure with a series of volumes less than the IC and plot a graph relating lung inflation with pressure. From the graph find the combined compliance in litres per cm water pressure.

3·16 Gas Analysis

For many years the most widely used method for the measurement of respiratory gases has been the Haldane procedure. Many modifications have been introduced but they all use the same basic principle. A volume of gas is measured in a calibrated burette; it is then exposed to potassium hydroxide which absorbs the carbon dioxide and the reduced volume is then measured, so giving the percentage of carbon dioxide originally present. The gas sample can next be exposed to pyrogallic acid which will absorb the oxygen present and the sample volume, now further reduced, can again be measured. The second reduction in volume will give the percentage of oxygen present in the original sample, and the volume remaining gives the percentage of nitrogen.

A sample of atmospheric air is easily obtained and a sample of expired air can be obtained by connecting a collecting bag to the expiratory side of mouthpiece and one-way valve system. The collection of alveolar air is a little more difficult. As expired air is a mixture of dead space air and alveolar air, if we could discard the first part of an expiration, a sample from the second part would give us alveolar air. This holds good only if we are dealing with a normal person with even air distribution in the lungs. The separation of the sample can be arranged if the subject exhales into a 1.3 m long tube. At the end of expiration the air in the tube at the mouthpiece end will be alveolar, and so a sample of alveolar air can be obtained at this point.

Fix a gas sampling tube in a clamp about 1 m above the table on a stand in the middle of a large tray. A mercury reservoir is connected to the lower end of the sampling tube by a length of pressure tubing. Turn the taps so that on raising the reservoir the sampling tube is filled with mercury and the air is completely expelled. Close the upper tap of the sampling tube and lower the mercury reservoir to table level. When the mercury has all run out of the sampling tube close the lower tap and disconnect the reservoir.

Sterilize the mouthpiece of the 1.3 m long tube and attach the sampling tube to the side tube near the mouthpiece. The subject breathes normally for a short time, then at the end of a normal inspiration puts his mouth to the mouthpiece, expires deeply and closes the mouthpiece with his tongue. The upper tap of the sampling tube is opened to admit the air sample and then closed.

Alveolar air is saturated with water vapour at body temperature (37° C); the water vapour pressure is about 47 mm. Hg. The tension of CO_2 and O_2 in the alveolar air is calculated thus:

$$P_{A_{CO_2}} = \frac{\% CO_2}{100} \times (\text{Barometric pressure} - 47)$$

$$P_{A_{O_2}} = \frac{\% O_2}{100} \times (\text{Barometric pressure} - 47)$$

Using the methods described in paras. 3.17 to 3.20 carry out an analysis of:

(a) Atmospheric air.

(b) Expired air.

(c) Alveolar air.

Now repeat experiment 3.9 and calculate your subject's respiratory quotient as well as his minute volume. The respiratory quotient is the ratio of CO_2 produced to O_2 consumed. It indicates the type of food being metabolized and by applying the nomograms 4.1 and 4.2 the subject's metabolic rate can be calculated.

The composition of atmospheric or inspired air is remarkably constant and values of,

$CO_2 = 0{\cdot}03$ per cent. $O_2 = 20{\cdot}93$ per cent. and $N_2 = 79{\cdot}04$ per cent. can be assumed. Besides measuring the total volume, V, in the Douglas bag analyse a sample of expired air for percentage content of CO_2, O_2 and N_2. Let these be $CO_{2\text{Exp.}}$ $O_{2\text{Exp.}}$ and $N_{2\text{Exp.}}$

$$\text{Then, } CO_2 \text{ produced} = \frac{[CO_{2\text{Exp.}} - 0{\cdot}03]V}{100} \qquad \ldots (1)$$

$$\text{Volume of } N_2 \text{ expired} = \frac{N_{2\text{Exp.}} \times V}{100}$$

$$= \text{Volume of } N_2 \text{ inspired, since this gas is not absorbed or excreted.}$$

But, each 79·04 ml. of N_2 in atmospheric air is accompanied by 20·93 ml. of O_2.

$$\therefore \text{ Volume of } O_2 \text{ inspired} = \frac{N_{2\text{Exp.}} \times V}{100} \times \frac{20{\cdot}93}{79{\cdot}04}$$

$$\text{and volume of } O_2 \text{ expired} = \frac{O_{2\text{Exp.}} \times V}{100}$$

$$\therefore O_2 \text{ consumption} = \frac{N_{2\text{Exp.}} \times V}{100} \times \frac{20{\cdot}93}{79{\cdot}04} - \frac{O_{2\text{Exp.}} \times V}{100}$$

$$= \frac{V}{100}\left[\frac{20{\cdot}93\, N_{2\text{Exp.}}}{79{\cdot}04} - O_{2\text{Exp.}}\right] \qquad \ldots (2)$$

From (1) and (2),

$$\text{R.Q.} = \frac{CO_2 \text{ produced}}{O_2 \text{ used}}$$

$$= \frac{V}{100}\left[CO_{2\text{Exp.}} - 0{\cdot}03\right] \Big/ \frac{V}{100}\left[\frac{20{\cdot}93\, N_{2\text{Exp.}}}{79{\cdot}04} - O_{2\text{Exp.}}\right]$$

$$= \frac{CO_{2\text{Exp.}} - 0{\cdot}03}{\dfrac{20{\cdot}93\, N_{2\text{Exp.}}}{79{\cdot}04} - O_{2\text{Exp.}}} \qquad \ldots (3)$$

To calculate metabolic rate the following steps must be taken:

1. From nomogram 4.1 find the calorific value of 1 litre of oxygen at the R.Q. obtained in equation (3).
2. Express the oxygen consumption in litres per minute at S.T.P.

3. From these values the heat output per minute is derived by multiplication.
4. With the help of nomogram 4.2 express this figure in kilocalories per square metre per hour.

In fact a great deal of the above calculation can be avoided. Thus, Figure 4.1 also includes a nomogram which by-passes the calculation of R.Q. and relates the kilocalorie value of a litre of expired air at N.T.P. to the percentage of oxygen in the expired air. Then, the heat output is obtained by multiplying the number of litres of expired air per minute at S.T.P. by the appropriate kilocalorie value per litre. The nomogram includes a protein correction, assuming that 10-15 per cent. of the dietary calorie intake arises from protein.

3.17 The Lloyd Modification of the Haldane Gas Analysis Apparatus

The use of this apparatus[2] will be demonstrated to you. It will yield accurate analyses of oxygen and carbon dioxide only after you have acquired skill in its use. Make analyses of atmospheric air until a result sufficiently close to 20·93 per cent. for O_2 and 0·05 per cent. for CO_2 is obtained. Then proceed to analyses of gases of unknown composition (Lloyd, B. B. (1958). *J. Physiol.* 143, 5-6*P*).

3.18 Estimation by the Modified Haldane Apparatus (Campbell's)

This apparatus[21] is now in widespread clinical use. An instruction sheet on the method of using it will be found with the instrument. Get a demonstrator to show you the method before you attempt it yourself.

3.19 Infra Red CO_2 Analyser

An even more rapid method of estimating carbon dioxide is also available, which has the added advantage of giving a continuous reading[18]. It works on the principle that infra-red radiation is absorbed by carbon dioxide in proportion to its concentration. A demonstrator will show it in use.

3.20 Paramagnetic Oxygen Meter

A device for measuring oxygen which is quicker and simpler than the Haldane apparatus is the paramagnetic oxygen analyser[18]. The principle on which this operates is the measurement of the magnetic susceptibility of O_2. Among respiratory gases O_2 is unique in being strongly paramagnetic (attracted in a magnetic field), whereas the others are slightly diamagnetic (repelled in a magnetic field). The analyser consists of a test body (a dumbell-shaped body of two small hollow glass spheres) suspended by a quartz fibre between two permanent magnets. The gas to be analysed surrounds the test body. Depending on the difference between the magnetic susceptibilities of the glass spheres and the gas which the sphere displaces, the test body swings in and out of the magnetic field until it reaches a position of equilibrium. A beam of light is reflected by a mirror attached to the test body on to a scale calibrated in O_2 percentages and tensions.

1. Insert the nozzle on the long pipe of the analyser into the gas to be analysed.
2. Squeeze the bulb six times, allowing it to expand fully each time.

3. Press the button on top of the analyser and read off the position of the light beam. This gives the oxygen percentage of the mixture analysed.

There are two analysers, one with a range of 0-25 per cent. and the other with a range of 0-100 per cent. The former will obviously be more accurate for the usual respiratory concentrations.

3.21 Dead Space Volume

Bohr developed an equation for the dead space volume from the fact that the total volume of expired gas is equal to the volume of the alveolar portion of gas and the volume of the dead space portion.

Using CO_2 as the gas we get the equation:

$$V_D = \frac{[F_{A_{CO_2}} - F_{E_{CO_2}}] \cancel{\dot{V}_E}}{F_{A_{CO_2}}} T.V.$$

Following a normal inspiration, breathe into a small collecting bag, measure the volume of expirate and its CO_2 concentration. Using the value already obtained from analysis of the subject's alveolar gas, calculate his dead space volume with the above formula.

In adults it has been found that the weight in pounds is approximately equal to the dead space volume in millilitres.

3.22 Indirect Method of Estimating Arterial P_{CO_2}

The arterial CO_2 tension (Pa_{CO_2}) serves as an excellent index of the adequacy of pulmonary ventilation, indeed the Pa_{CO_2} is so informative that it would be measured in a wide range of clinical conditions were it not for the technical difficulty of its measurement.

A re-breathing method has been devised, however, using the alveolar P_{CO_2} to estimate the arterial CO_2 tension. The basis of this technique is that if we bring into equilibrium the carbon dioxide in a bag, in the lungs and in the pulmonary capillaries, then an analysis of the CO_2 content of the bag will give us the CO_2 tension of the pulmonary capillary blood and in effect measure Pv_{CO_2}.

Method

1. Fill a 2-litre bag with approximately 1·5 to 2 litres of oxygen.

2. Insert the mouthpiece and apply a nose-clip. When the subject is breathing comfortably to and from the atmosphere, turn the sleeve valve so that he breathes to and from the bag. During the first few breaths, partially empty the bag if tidal volume is less than half the bag volume. Re-breathe for one and a half minutes, then close the sleeve valve with the bag full of gas.

3. Lay aside the bag for two minutes.

4. Re-breathe into the bag again for 20 seconds, then close the valve again with the bag full.

5. Analyse contents for CO_2 using the modified Haldane apparatus (Campbell's$_{21}$). Multiply the barometric pressure minus the water vapour pressure in the lungs (47 mm Hg) by the CO_2 percentage. The answer is the tension of CO_2 in the bag. The arterial CO_2 tension is obtained by subtracting 6 mm Hg from the bag tension.

3·23 Breath Sounds

By means of a microphone and loudspeaker the sounds caused by passage of air into and out of the chest will be demonstrated. Listen with a stethoscope over the trachea for bronchial breathing and in the axilla for vesicular breathing and try to appreciate the differences between the two as described by the demonstrator.

3·24 Respiratory Patterns

As respiratory movements reflect respiratory adjustments, a study of these movements is of interest. A useful method of studying these movements which does not interfere with speech or ingestion, is by means of a stethograph or pneumograph. This consists of a corrugated rubber hose-pipe with a stopper in each end and an air outlet pipe to a recording tambour.

Adjust the stethograph around the subject's chest, connect the side tube to the tambour, adjust the amount of air in the system and the position of the corrugated tube on the chest in order to get the maximum response to respiration. Have the subject sitting with his back to the recording drum and then observe respirations in terms of rate, rhythm and amplitude under different conditions.

1. *Normal Respirations.* Record normal respirations on a drum (speed of about 2·5 cm to each respiratory cycle) for about three minutes. Then run a time-trace on the drum. Note the characteristics of the trace such as the rate, the relative duration of inspiration and expiration, presence or absence of a pause between inspiration and expiration or between expiration and inspiration.

2. *The Effect of Swallowing.* The subject takes a mouthful of water and holds it in his mouth without swallowing, while breathing through his nose. Make a record of normal respiration and at the command 'swallow', the mouthful is swallowed and a mark is made on the tracing. A more striking effect is obtained if the subject drinks a beaker (250 ml.) of water in a continuous swallowing movement. Record the respiratory movements before drinking, during the swallowing, and then in the subsequent half minute.

3. *The Effect of Talking.* Record normal respiration and then get the subject to read a passage from a book, e.g. a speech from Shakespeare.

4. *Abdominal and Chest Movements.* With two stethographs record abdominal and chest movements simultaneously. Attempt to inhibit abdominal movement during respiration.

3.25 Breath-holding

1. Sit quietly for three to four minutes, breathing normally, then hold breath for as long as possible. How long can the breath be held? Find the average of three trials.

2. After one to two minutes of forced breathing (try to increase the depth rather than the rate of respiration) find how long the breath can be held.

3. With the nose-clip in position, re-breathe for one minute from a small bag. Then find how long the breath can be held.

4. After two to three minutes quiet breathing, take a deep breath, and at the end of inspiration hold the breath. Is the resulting urge to breathe expiratory or inspiratory? Repeat the experiment but exhale deeply and then hold your breath.

5. Place one end of a short glass tube in water and the other in your mouth, then hold your breath. When breaking point is reached, sip water.

Try to account for all your results.

EFFECTS OF CO_2 EXCESS OR LACK

3.26 CO_2 Inhalation from Douglas Bag

Fill a Douglas bag with 5 per cent. CO_2, 95 per cent. O_2 mixture from a cylinder. Connect a valved mouthpiece assembly (Fig. 3.4) so that the subject will inspire the gas mixture and expire it into a second empty Douglas bag. Record the respiratory movements with a stethograph and find the average minute volume during inhalation. Compare with your resting minute volume while breathing room air.

3.27 Breath-holding after Hyperpnoea and Exercise

Fit a stethograph and record respirations on a slow drum (about two respirations per cm). The subject must not be allowed to see the drum during the experiment.

1. Take a trace of, say, six normal respirations; while the drum is still running, the subject, at the order of the observer, holds his nostrils and stops breathing; after a time it will be impossible for the subject to hold the breath any longer; continue to record respirations till they return to normal. The subject should try to avoid modifying his respirations voluntarily and should keep his mind off his rate and mode of breathing. This also applies to sections 2 and 3 below.

2. Take a short record of normal respirations; swing the lever off the drum and then take a series of very deep respirations for two or three minutes; return the lever to the drum and record the last two or three deep breaths; then hold the breath as long as possible and record the effect as before.

3. Take a short record of normal respirations as a standard. Swing the lever off the drum and do standing running for two to three minutes. Swing the lever back on to the drum, record two or three breaths, hold the breath as long as possible and record the effect.

Run a time-trace. Measure the periods of apnoea, calculate the respiratory rates under the various circumstances and interpret the results.

3·28 The Effect of Forced Hyperpnoea on Spontaneous Respiration

Open the side tube of the stethograph and instruct the subject to take full inspirations as deeply and rapidly as possible. Inspiration only should be forced; expiration is allowed to occur naturally (i.e. not forced). This is continued for exactly one minute when the subject is told to stop and to pay no further attention to his breathing. Immediately clip the side tube of the stethograph and begin to record the respiratory movements. There is sometimes a phase of apnoea and then, when the respiration does begin again, it is usually irregular and often 'periodic', i.e. it alternately waxes and wanes (Cheyne-Stokes respiration). Record any changes in the colour of the subject during the period of over-breathing and during the recovery period. The subject should then describe his sensations during the overbreathing and during the recovery period and a careful note should be made of these. Pay particular attention to the occurrence of tingling or cramp in the muscles and spontaneous twitching of muscles. Discuss your results.

3·29 Effects of CO_2 Excess

Records of the effects caused by breathing air containing an increasing percentage of CO_2 can be obtained with the aid of a spirometer.

The soda-lime tower is removed from the spirometer so that CO_2 will not be absorbed and approximately 4 litres of oxygen is added. The subject, with a nose-clip on, inserts the mouthpiece and breathes to and from the atmosphere until his respiration becomes steady. The tap is then turned so that the subject breathes to and from the spirometer. Take a record for five to six minutes but stop if the panting becomes intolerable. There will be no oxygen lack but a build-up in concentration of carbon dioxide will occur. The subject should describe his sensations. Discuss these and the record you obtain.

3·30 Effects of O_2 Lack

Care should be taken with this experiment demonstrating the effects of oxygen lack and a member of staff should be present as people vary in their sensitivity to lack of oxygen. When cyanosis is seen the experiment is terminated even if little change is seen on the breathing record.

Empty the spirometer of gas, insert the soda-lime canister for absorption of CO_2 and fill the spirometer with room air. Repeat the experiment as in 3.29. As the subject breathes to and from the spirometer, the oxygen content will fall fairly quickly as oxygen is being consumed, but because of the presence of the soda-lime there will be no accumulation of carbon dioxide in the system. Again, the subject describes his sensations and you should discuss these and the record obtained.

3·31 The Effects of Combined CO_2 Excess and O_2 Lack

The combined effects of a diminishing concentration of oxygen and a rising level of carbon dioxide on the pattern of respiration can also be shown with the spirometer. The soda-lime absorber is removed and the spirometer is filled with room air. The experiment is then repeated as before. This time the enhanced effect will probably result in making the subject terminate the experiment earlier.

3·32 Artificial Respiration

It is obviously most important that everyone should be able to perform artificial respiration efficiently in an emergency. The situations in which it is required are drowning, electric shock, overdose of narcotics or anaesthetics and the inhalation of poisonous or non-respirable gases. The method most favoured now is that of mouth-to-mouth respiration described below.

Mouth-to-mouth respiration is taught with the aid of a practice mannikin. Get a demonstrator to show you the technique. In addition a film may be shown.

The first step in resuscitation of a subject who is not breathing is to provide a clear air passage. This is done by hyperextending the head and pulling up the chin. This ensures that the base of the tongue is pulled away from the posterior pharyngeal wall. The head is maintained in this position throughout the whole procedure.

Next the nostrils are pinched between the finger and thumb, the rescuer opens his mouth widely and places his lips round the victim's mouth making as tight a seal as possible, and the victim's lower lip is pulled down in order to open his lips.

The rescuer then blows air into the victim's lungs until the chest is seen to expand fully. If the chest does not rise, then one looks for the cause of obstruction. Any foreign matter is removed and if none is present, the head should be extended further, the chin pulled again and another attempt made to blow air into the lungs.

When the chest has expanded fully, the rescuer removes his mouth in order to take another breath, and the victim's head is held in the same position so that the elastic recoil of his chest will empty the lungs.

This intermittent inflation is continued at a rate of approximately 15 times a minute until spontaneous respiration is resumed. The rescuer should attempt to use twice his normal tidal volume for ventilation of the subject.

If the colour of the patient's skin does not improve, a check should be made on his circulation. An imperceptible pulse and dilated pupils mean that the circulation is inadequate and external cardiac massage should be started. Pressure with the heel of the hand on the lower end of the sternum, sufficient to depress it about 3 to 5 cm is repeated once a second. This will produce an adequate circulation as long as it is continued. This procedure too should only be practised on the mannikin and will be demonstrated by a member of staff.

CHAPTER FOUR

METABOLIC RATE AND BODY TEMPERATURE

Metabolic rate is the rate of production of free energy in the body. It is assumed that this is all in the form of heat and it is expressed as kilocalories per hour. Since the direct measurement of heat production from the whole body involves very cumbersome and expensive apparatus, this method has been reserved to check the validity of indirect methods. Indirect methods use measurement of oxygen consumption as an indicator of heat liberation.

It is necessary to specify the conditions in which the measurement is made. The Basal Metabolic Rate (BMR) is taken as the heat liberation when the subject lies quietly after a night's sleep and at least 12 hours after a meal; in practice this means a measurement first thing in the morning before breakfast. These conditions usually cannot be met by the members of a practical course and, as a compromise, the experiment is conducted as though basal conditions applied. This introduces the student to the practical details of the estimation and the actual result obtained is not taken too seriously.

4.1 Metabolic Rate Estimation by Open-circuit Method

Expired air is collected over a timed period in a Douglas bag$_{12}$, its volume is measured and its composition found by analysis. From these measurements the oxygen consumption per minute and the respiratory quotient are obtained. The respiratory quotient indicates the type of fuel being burnt and gives the calorific value of oxygen.

Procedure

Fit the mouthpiece, which has inlet and outlet valves (Fig. 3.4) to the subject. Apply a nose-clip; test for leaks. Connect the outlet valve to an empty Douglas bag and time the collection period necessary to three-quarters fill the bag. Mix the contents of the bag and expel a little air through the side tube to clear it of atmospheric air. Withdraw an expired-air sample either into an evacuated glass gas-sampling tube (see 3.16) or an oiled all-glass syringe (30 or 50 ml.). These samples must be withdrawn within 10 minutes of the end of the collection period, because many bags have a differential leak for oxygen and carbon dioxide. Pass the gas steadily out of the bag

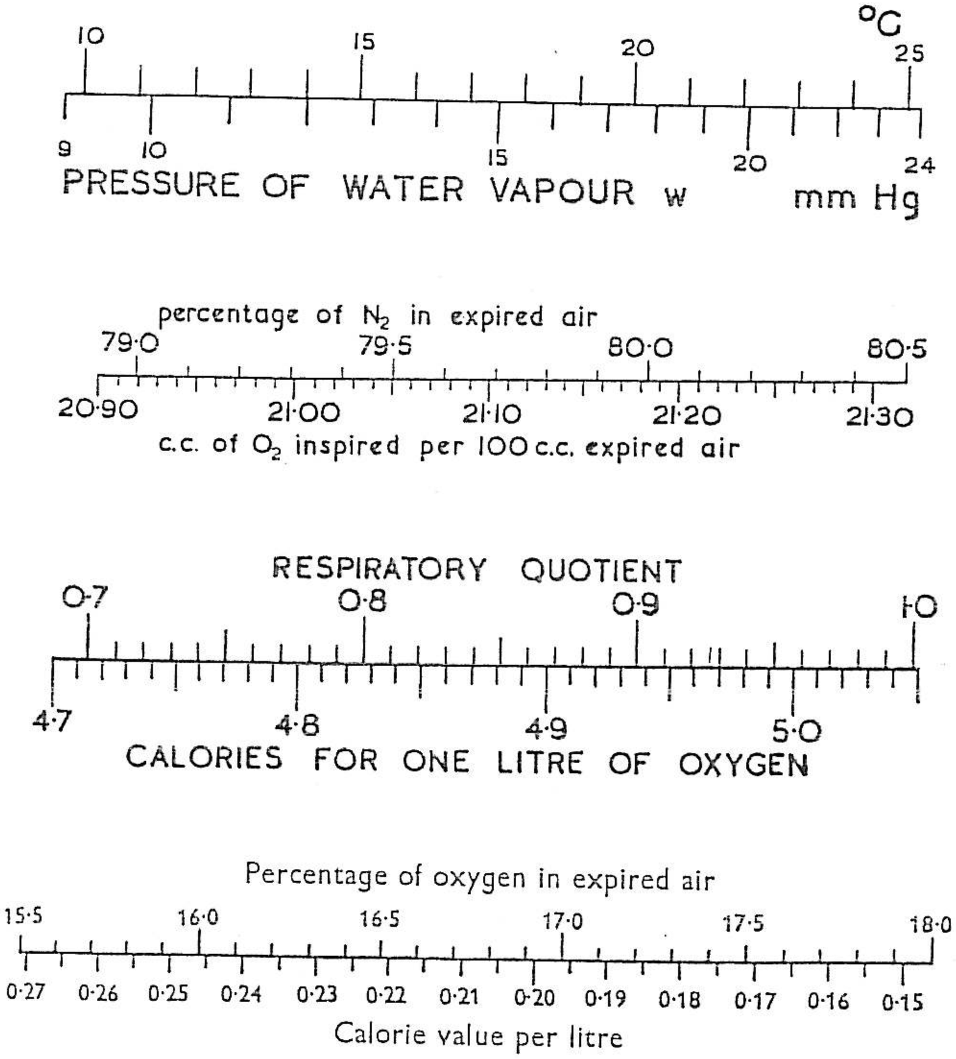


FIG. 4.1

From the percentage of oxygen in expired air, this nomogram gives the Calorie value per litre of expired air. The heat output is given by multiplying the number of litres of expired air by the Calorie value per litre. A protein correction is included on the assumption that 10-15 per cent. of the total Calories arise from protein metabolism. (Weir, J. B. de V. (1949). *J. Physiol.*, 109, 1). The word Calorie used here is the large calorie or kilocalorie.

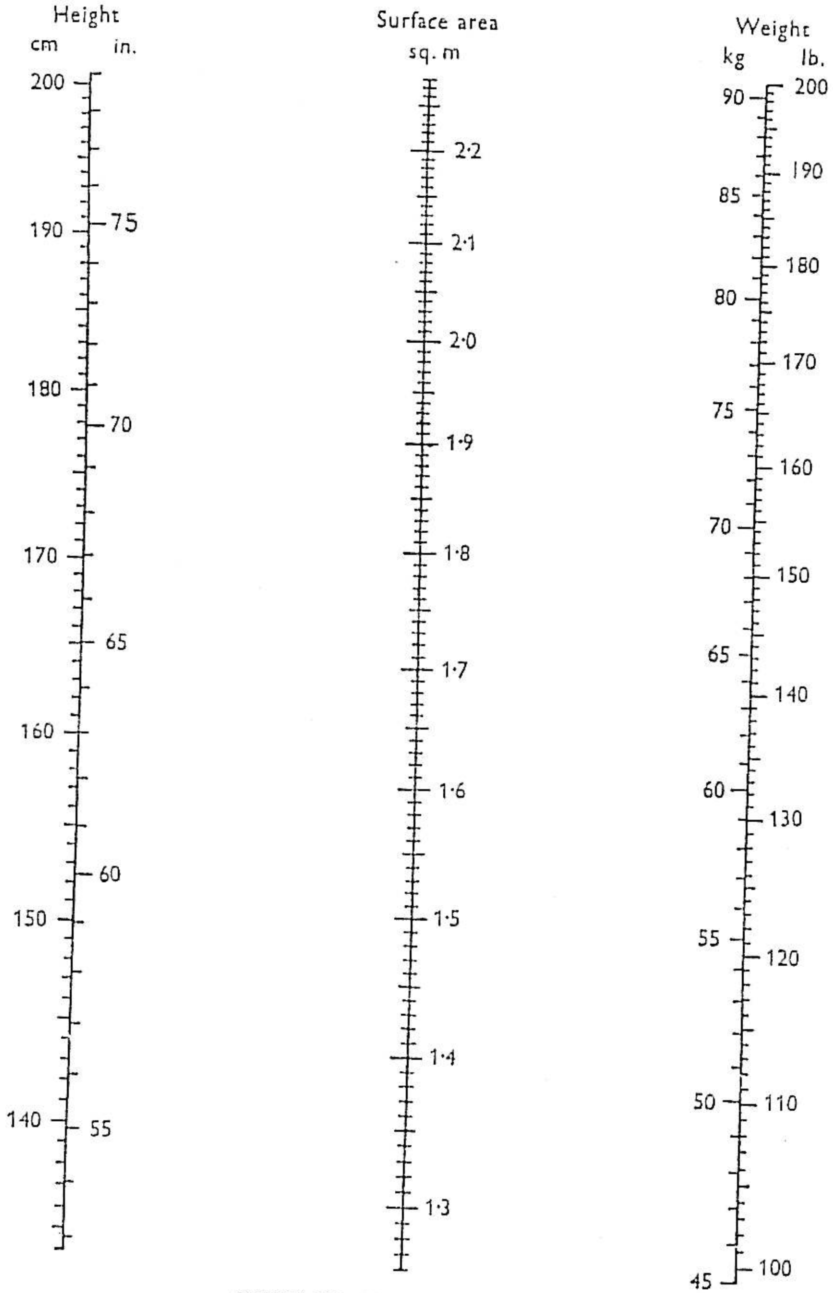
through a gas meter, within the permitted range of flow rate for the particular meter used, which is marked on the meter. Find the average minute ventilation rate by dividing the gas volume in the bag by the collection time in minutes. Convert the volume to standard temperature and pressure by Nomogram 3.2. Analyse the gas sample by an accurate method, such as the Lloyd modification of the Haldane gas analysis apparatus (3.17). Calculate the respiratory quotient (3.16) and the oxygen consumption. The R.Q. should be between 0·8 and 0·9. Find the calorific value of oxygen at the calculated R.Q. from Nomogram 4.1. Measure the subject's height and weight and find his estimated surface area with the aid of Nomogram 4.2. Express your answer as kilocalories per sq. metre body surface per hour.

4.2 Estimation of Metabolic Rate by Closed-circuit Method. The Benedict-Roth Apparatus

This apparatus is used clinically where approximate values of the metabolic rate are sufficient. It records the respiratory movements and oxygen consumption graphically. Expired carbon dioxide is removed from the circuit by soda-lime reabsorption. The apparatus, one form of which is shown in Figure 4.3 consists of a light cylindrical metal bell which fits loosely into a narrow space between two concentric cylinders; the water which fills this space forms an airtight seal but allows free movement. The bell is counterpoised by a weight connected to it by a chain which runs over a pulley. In this way the bell can move freely to accommodate the oxygen within it at atmospheric pressure. An ink-writing pen attached to the counterpoise weight records the volume of gas in the bell on a specially printed chart calibrated with horizontal lines for volume and vertical lines for time.

The bell is first filled with oxygen from a cylinder provided with a reducing valve. The subject is then connected to the apparatus by two large diameter tubes inserted into a mouthpiece. The nose is clipped and he inspires oxygen from the bell through one tube and expires through the other tube through soda-lime and back into the bell, backflow of gas being prevented by valves. The respiratory circuit is thus cut off entirely from the outside air. The bell moves up and down with each respiration and slowly sinks as the oxygen is used up. The rate of fall measures the rate of oxygen consumption. While the apparatus is being prepared the subject should rest on the couch. The operation of two models of this apparatus, the Palmer and the Kendrick, will be described.

The Palmer Apparatus. Note the position of the CO_2-absorber; it may be either a cylindrical canister fitted with a flutter valve which screws into position within the spirometer, or it may be a metal box fitted with a low-resistance flap valve inserted in the air-line between the mouth-piece and the spirometer. In either case fill the canister with soda-lime$_9$. This is coloured green or blue when fresh and changes to orange when its absorbent capacity is exhausted. Fill the outer cylinder with water to create the air seal, open the oxygen inlet tap, and gently push down the bell. Fit a record paper to the drum. Clear the ink-writer with a stilette and fill the reservoir with ink. Fill the



SURFACE AREA NOMOGRAM

FIG. 4.2

(Weir, J. B. de V. (1949). *J. Physiol.*, 109, 1).

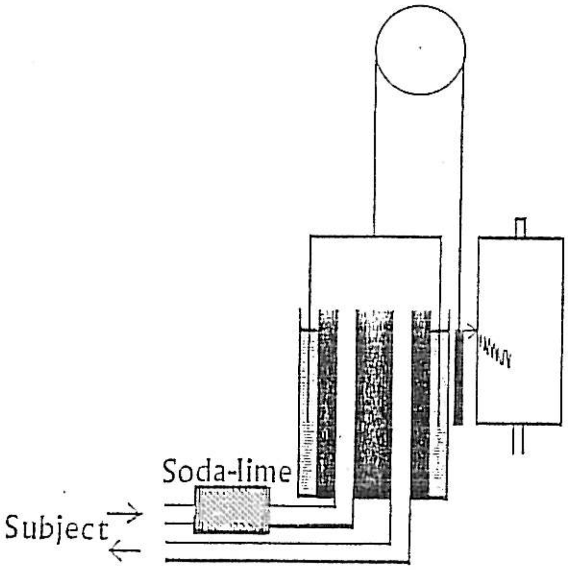


FIG. 4.3

no fluid enters the tubes. Place the mouthpiece in the subject's mouth and clip his nose; the subject thus breathes through the mouthpiece to the air. The nose-clip must be properly adjusted since a slight leak through the nose can cause large errors. The subject should be made perfectly comfortable, given a book to read and left undisturbed for at least 10 minutes. When he has settled down turn the mouthpiece tap during inspiration through 90° so that he now inspires oxygen from the spirometer.

The drum is now started and the writing pointer applied. If the pointer is travelling below the level of the lower edge of the drum wait until it has risen above this level before applying it to the drum. Continue the record until the spirometer is nearly empty, then remove the mouthpiece and stop the drum.

Calculations

The same type of record is obtained from the two models and the calculation is identical.

Ignore the first five minutes of the record. During this period breathing is sometimes irregular as the subject accustoms himself to the increased air-flow resistance due to the valves and CO_2-absorber. There is also a phase of equilibration to the high oxygen, low nitrogen composition of the inspired air. Although the spirometer is filled with pure oxygen, nitrogen is contributed from the subject's lungs and body so that pure oxygen is not breathed during the test.

Make your measurements on the later part of the record.

On the chart put: Name of subject, age, height in cm, weight in kg., pulse rate, respiration rate (count from chart), volume of oxygen used in certain time. The rate of oxygen consumption may be found by laying a ruler along the latter part of the record and finding the slope of a line which matches the inclination. If the tidal volume remains constant it is convenient to lay the ruler along the lower turning points corresponding to beginning of inspiration. If the tidal volume is variable draw a line along the mid-points of the tidal excursions. Express the slope of the line in ml. O_2 per minute. A steadily increasing tidal volume may mean that CO_2 is accumulating in the circuit in which case the soda-lime should be replaced. Measure the barometric pressure and the spirometer temperature. Use the Nomogram 3.2 to find the corrected volume of oxygen consumption per minute at S.T.P. Find the volume of oxygen used at S.T.P. in (*a*) 1 hour (*b*) 24 hours. At an R.Q. of 0·82, 1 litre of oxygen at S.T.P. has a kilocalorie value of 4·85. Express (*a*) and (*b*) in kilocalories. Find the body surface area of the subject from Figure 4.2 and calculate kilocalories per sq. metre body surface per hour. Look at Table 4.1 to see the range of B.M.R. values. If your test has been conducted under strict basal conditions, express your answer as a percentage of the normal.

Table 4.1

Basal Metabolic Rate

Kilocalories/sq. metre body surface/hour

Age	Male	Female
18	40	36
20	38·6	35·3
25	37·5	35·2
30	36·8	35·1
35	36·5	35·0
40	36·3	34·9
45	36·2	34·5

4·3 The Specific Dynamic Action of Food

The subject should come to the laboratory in the morning without having any breakfast. He rests for half an hour and then his metabolic rate is measured as described in paragraph 4.2. He then eats a good breakfast which has been prepared for him during the metabolic rate estimation. The composition of the breakfast should be decided by the subject. The subject again rests on the couch and his metabolic rate is measured 30 and 60 minutes after the meal. If time permits, further estimations may be made. Calculate the values of metabolic rate as kilocalories per sq. metre body surface per hour and express as percentages of the initial (pre-breakfast) value. Estimate, with the aid of food tables, the composition and kilocalorific value of the meal.

4·4 Metabolic Rate during Work

When measuring oxygen consumption during work it is important that the apparatus does not harass the subject or modify his normal posture and work procedure. Examine the portable respirometer provided (Kofranyi-Michaelis$_{13}$). It is a light gas meter which is accurate over the range of expired air-flow encountered in the working subject and offers little resistance to breathing. It contains a device which samples the expired air throughout the measurement period and collects the sample in a small rubber bladder. A light-weight mouthpiece assembly with inlet and outlet valves is connected to the gas meter by a rubber airway.

Strap the gas meter on the subject's back, fit the mouthpiece assembly to the subject and apply a nose-clip. Allow the subject several minutes to accustom himself to the apparatus before starting the work task. Read the meter and thermometer, start the stopclock, engage the meter recording mechanism and begin the task. Measure the barometric pressure at the end of the task, disengage the meter mechanism, note the time, read the meter, and temperature. Disconnect the sample collection bladder and as soon as possible analyse the expired air by an accurate method, such as the Lloyd modification of the Haldane gas analysis apparatus (see 3.17). Correct the expired air volume to S.T.P. and use the Nomogram 4.1 to obtain the calorific value per litre of expired air. Calculate the subject's metabolic rate in kilocalories per hour.

BODY TEMPERATURE

Under normal conditions the body temperature of man remains relatively constant within the limits 97° to 99° F, or 36° to 37° C. There is a diurnal variation of about 2° F or 1° C, the maximum occurring in the early evening and the minimum in the early morning. Prolonged muscular exercise may cause a rise of 2° or 3° F but apart from this the temperature in health usually remains within the limits stated.

The temperature may be taken in the mouth, axilla, or rectum. The rectal temperature is the highest (0·5° F above mouth temperature) and is usually regarded as the most reliable. The axillary temperature is not very reliable especially in thin persons. The mouth temperature is reliable, provided that the thermometer is kept there for several minutes. Hot or cold drinks may, however, affect the mouth temperature to a considerable extent.

4·5 Measurement of Body Temperature

The clinical thermometers are left standing in a jar of antiseptic solution (non-poisonous). After use they are washed under the *cold* water tap and replaced in the solution. The glass of the thermometer stem is shaped to act as a convex lens and gives a magnified image of the mercury column. Since this image is visible only from one particular angle the thermometer should be rotated slowly until the mercury comes into view.

1. Hold the thermometer by the end away from the bulb and shake the mercury down. Place the bulb under the tongue and close the mouth. After exactly half a minute take out the thermometer and record the reading. Shake the mercury down again; put the thermometer back in the mouth and let it stay for one minute before removing to take the reading. Continue in this way to take readings after 1½, 2, 2½ minutes and so on until a constant reading is obtained. Plot the results. If it is assumed that the highest temperature reached is a true reading of body temperature how long must the thermometer be kept in the mouth?

2. Take a mouthful of *cold* water, move it well around the mouth and then swallow it. Repeat this several times then take the mouth temperature, leaving the thermometer in for the length of time previously found to be adequate. How does this reading compare with that recorded in (1)?

3. Axillary temperature. Place the thermometer in the axilla and hold it tightly in place for three minutes. Record the reading and account for any difference between it and the mouth temperature.

bell with oxygen from the cylinder by attaching a rubber tube to the oxygen inlet tap at the base of the spirometer. Close this tap and remove the tubing. Open the mouthpiece assembly valve to atmospheric air. Bring the ink-writer against the drum surface at the zero time line. Test that the ink is flowing freely. The mouthpiece, which is a flanged rubber tube, has been stored in dilute, non-poisonous antiseptic solution, it should now be washed under the tap and fitted to the mouthpiece assembly. The subject, still resting on the couch, is now asked to lie supine, his head supported by a pillow. The mouthpiece assembly is positioned so that the rubber flange fits between the subject's teeth and lips. He grips the rubber blocks projecting from the flange with his teeth and presses his lips inwards on the flange to prevent air leaks. As the mouthpiece assembly valve is open to the air the spirometer does not move and the subject is encouraged to relax for a further five minutes. He should be quite passive and pay no attention to the proceedings. Apply the noseclip to the subject and satisfy yourself that the mouthpiece is correctly positioned. Start the drum motor and close the valve on the mouthpiece assembly at the end of an expiratory movement. The subject's lungs and the spirometer now form a closed-circuit. Sometime during the next five minutes take the subject's pulse at the wrist. When the pen is nearly at the end of the chart, or when the oxygen is almost exhausted, open the valve on the mouthpiece assembly to atmospheric air. Read the air temperature. Release the subject. Swing the ink-writer off the drum and remove the chart.

Kendrick Apparatus. Remove the drum from the drum carrier and wrap a sheet of recording paper around it fixing the overlapping edge with two pieces of gummed paper. Replace it in the drum carrier. Fill the ink reservoir of the ink-writing pointer and see that the pointer writes when it is moved on the paper; it may be necessary to clean out the writing tube with a fine wire to make the ink flow. The drum is driven by an electric clock which is controlled by a switch on the clock. As the peripheral speed of the drum is only about 2·5 cm per minute it is difficult to tell whether it is moving or not unless the pointer is put against the paper. The rate is such that it takes exactly one minute for the pointer to pass between two vertical red lines. It is most important *not* to lift off or replace the drum on the drum carrier whilst the motor (clock) is running. Further the drum must not be turned by hand while it is on the carrier. If it is necessary to alter the position of the drum stop the motor; then lift the drum off and replace it in the required position.

Connect the valves and the large bore tubing to the mouthpiece and spirometer and turn the tap above the mouthpiece so that there is no communication between the spirometer bell and the outside air. Open the oxygen inlet tap and then empty the spirometer by *slowly* and *gently* pressing down the bell. Fill the spirometer with oxygen from the cylinder (see 3.2). While the oxygen is being run in make sure that the mouthpiece tap is set so that oxygen cannot escape along the inspiratory tube. When the spirometer is full shut off the oxygen cylinder and close the oxygen inlet tap.

The subject should lie down on the couch with his head well propped up. Wipe the mouthpiece with a piece of gauze wrung out in the antiseptic fluid; be careful that

Engström MIE **MATERIAL SAFETY DATA SHEET**

Subject: *Durasorb*™ Soda Lime

Introduction:

Durasorb™ is a Trade Name of Engström MIE and is used in closed circuit anaesthetic breathing systems to absorb the expired Carbon Dioxide (CO_2).

Durasorb™ contains a colour indicator which changes from **PINK** to **WHITE** when its CO_2 absorption properties are exhausted.

Description: Granules

Chemical Constituents: *Durasorb*™ contains the following ingredients -

Calcium Hydroxide, $Ca(OH)_2$

Sodium Hydroxide, $NaOH$

Clayton Yellow

Water

(*Durasorb*™ is manufactured to B.P and U.S.P specifications.)

SAFETY PRECAUTIONS

- Do not freeze.
- Avoid direct inhalation.
- If in contact with the eyes - wash immediately with copious amounts of water and seek medical advice.
- If spilt - brush up the spillage and wash the area with generous amounts of water.
- Before use with new anaesthetic agents - check for reaction with sodalime.
- Dispose used *Durasorb*™ immediately after use - (it will return to its original colour if left for a period of time.)
- Dispose of used *Durasorb*™ in suitable, well-labelled containers, in accordance with the current environmental protection legislation for removal by a registered contractor and disposal at an approved site.

OR

- Provided the used / waste material has not been used with flammable agents, it may be safely incinerated. (Incineration converts any residual alkalinity in the material to produce a mixture of sodium and calcium carbonate. This may be disposed as normal for solid residues from incineration.)
- Trichlorethylene ('Trilene') must not be used with *Durasorb*™.

STORAGE INTRUCTIONS

- Do not freeze.
- Store in a cool, dark place and keep away from water.
- Protect the packaging from crushing.

APRIL, 1994

SPARES LIST FOR 9 LITRE SPIROMETER (50 1817)

50 0959	MOUTHPIECE
50 0967	NOSECLIP
50 1098	SODA LIME
50 1841	PRINTED CHARTS (PK 100)
50 7806	SPARE PEN ARM
50 7814	DISPOSABLE CARTRIDGE PENS (PK 6)