completely; the soft tissue surrounding the explant grew as vigorously as in the controls cultivated in normal medium.

The same results were produced by similar concentrations of an alcoholic extract of avoileum, a commercial preparation rich in vitamin A, made from liver.

Similar concentrations of vitamin A obtained by using plasma from fowls fed on a diet rich in the vitamin had a much less drastic effect on the explants.

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Speaking at the fourth annual conference dinner of the Society of Radiographers, Sir Andrew Davidson, Chief Medical Officer, Department of Health for Scotland, said that the Health Service Acts had made profound changes in the administration of the health services—changes made necessary mainly because of new and progressive trends in medical science and a fuller appreciation of the social, economic, and industrial effects of sickness and disability. There were many gaps to be filled and many deficiencies to be repaired. The new health service claimed to be doing that. Many agreed that the changes had brought real and appreciable public benefits; but they heard less of them than of the weaknesses. The new arrangements had immensely widened the opportunities for the prevention and treatment of ill-health wherever it arose. But could they take advantage of the opportunities? It was of great advantage that Scotland was not too large to prevent personal contacts, yet large enough to be able to maintain a full range of service. Important also was the happy circumstance that they had four flourishing medical university centres, all of the first rank, which together produced about one-third of the new doctors in the United Kingdom. It was fortunate also that the pattern for medical care in rural districts had been set up by the Highlands and Islands Medical Service. Again, Scotland had a well-developed public health service in the counties and burghs. It was too early to make any general assessment of positive achievements, but two facts stood out: (1) The Service has been accepted and indeed welcomed by the public, as 97% of the population are included on doctors' lists; and (2) those who were concerned in operating the Service were making strenuous and helpful efforts to make it a success. The proper balance between the various elements of the Service must be struck. More attention would need to be paid to those working in the homes of the people, whether they were concerned with prevention or cure. The co-operation of the public was needed on how to use the Service. Abuses would destroy it. Doctors had told him that much of the expenditure on expensive drugs was in response to demands by many patients for what they themselves wanted. Surely that was wrong. The public should not regard the Service merely as a machine which would turn out medicine, or spectacles, or dentures, or any other apparatus on demand.

RESPIRATORY STUDIES IN PARALYTIC POLIOMYELITIS

BY

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The following notes are based on studies at the Western Hospital, Fulham, by two of us (L. M. T. and E. D. J.) during the 1949 epidemic of poliomyelitis, and on laboratory studies at Stoke Mandeville Hospital. While many of the conclusions are tentative, it has become clear that there is much need for improvement in both the design and use of breathing machines. These notes are published in the hope of facilitating such improvement.

The tidal air of a patient in an iron lung can be measured without difficulty by the use of a spirometer of the type commonly employed in hospitals for the measurement of basal metabolism. There are, however, few published measurements of this type in cases of poliomyelitis, and very few detailed measurements taken from patients in tank respirators. Drinker and Shaw (1929) and Shaw and Drinker (1929) showed that in healthy subjects in tank respirators it was easy to produce a large tidal air with minute volumes of over 20 litres a minute at pressures of 20 cm. of water. Elam (1948) showed figures for six cases of poliomyelitis in respirators, but gave few details of the patients' condition. Binet, Bochet, and Bour (1948) gave figures for one patient and four healthy subjects.

Our studies have been concerned chiefly with the effects on tidal air and minute volumes of varying respirator suction pressures and stroke frequency. We have also studied the effects of varying the patient's posture while in a respirator, and the changes occurring in convalescent patients during and after weaning from their respirators. These experiences have indicated a need for a number of alterations in the Both type of respirator, which are discussed later.

Technique

1. *Spirometers*.—A commercial spirometer, using a rubber bellows instead of a float, was found to give too high a resistance to air flow for accurate work. A spirometer of the water-sealed gasometer type was therefore constructed. The counterweight guides and pulley were fitted with ball-races to reduce friction, and thus the pressure required to start the spirometer moving was reduced to only 2 mm. H₂O. As the spirometer was required to measure much smaller tidal airs than normal, the counterweight pulley system was designed to give an optional multiplication ($\times 2$) of the float movement. The sensitivity when this was used was 3.67 in. (9.32 cm.) per litre. The spirometer included an absorbent for CO₂, and was refilled with pure oxygen as and when necessary.

2. *Recording Drum*.—The recording drum used with this spirometer was 12 in. (30 cm.) in diameter and 16 in. (40 cm.) high, and gave paper speeds variable at will from about 2 in. (5 cm.) a minute to 1 in. (2.5 cm.) a second. The highest speed was adequate to display clearly the wave-form of each respiration.

3. *Recording Pressure Gauge*.—A recording pressure gauge was constructed by modifying an ex-R.A.F. air-speed indicator. This gave a pen movement of about 1.75 mm. per cm. water gauge. The time constant of the instrument was less than 1/20 second, so that its response was fast enough to record all details of the pressure waveform of the respirators. The pressures were recorded on the same drum as the spirometer, so that simultaneous records of respirator pressure and tidal air were obtained.

4. *Alveolar CO₂*.—This was estimated by a Haldane gas analysis apparatus after collection in sampling tubes by the method of Haldane and Priestley (1935).

5. To avoid leakage all measurements of tidal air were made with a nose-clip and a rubber mouthpiece having a flange between the patient's lips and teeth.

Glossary

We use the terms listed below as follows :

Carina. The bifurcation of the trachea.

Hypocapnia. A condition with a subnormal concentration of carbon dioxide in the blood.

Minute volume. The volume of air inhaled or exhaled during one minute.

Regression line (as used in Fig. 2). The calculated straight line for which the sum of the squares of the deviations of volume from the line is a minimum.

Reserve air (= supplemental air). The volume of air which the subject can expel with an effort after the end of a normal expiration.

Tank respirator. A breathing machine in which the whole of the patient's trunk and limbs are enclosed in a nearly rigid box.

Tidal air. The volume of air inhaled or exhaled during a single respiration.

Vital capacity. The maximal volume of air which a subject can exhale after the fullest possible inspiration.

All volumes quoted in this paper are measured at approximately 18° C. and include water vapour at approximately 15.5 mm. Hg.

Subjects Tested

Among the subjects studied were nine patients for whom respirator treatment was considered essential. Five of these were considered too ill for experimental tests and died without having had any measurements of tidal air. Particulars of the four surviving respirator cases and of the healthy subjects studied are given in Table I (M. C. and D. P. died in June and July, 1950).

Measurements of Tidal Air in Respirators

Effect of Negative Pressures on Tidal Air

About 600 measurements of tidal air were made and correlated with the amount of negative pressure in the Both and Drinker respirators. The results showed wide variations, both between different persons and from day to day in the same person. Fig. 1 shows curves relating negative

FIG. 1.—Tidal air and respirator suction pressure in two healthy adults. Rate of pressure change approximately 20 cm. H₂O a minute (too rapid for equilibrium). Circles show points measured with rising suction pressure, crosses those when pressure was falling. Respirator frequency 20 cycles a minute. Peak positive pressures 2 cm. H₂O.

pressure to tidal air in two healthy subjects. It was found easy to obtain smooth curves of this type by altering the pressure quickly so that unconscious physiological adjustments of the respiration rate did not have time to cause major alterations in the tidal air. In contrast to this, Fig. 2 shows points observed in other tests after the respirator adjusting valves had been left unaltered for a time sufficient for the tidal air to appear constant—usually at least one minute after any changes of pressure. These graphs show all tests of this type made at a respirator

TABLE I.—Particulars of Subjects Studied in Respirators

Initials	Sex	Age	Height approx.	Weight	Respiratory Muscles Paralysed, and Date of Onset	Total No. of Days in Respirator	Vital Capacity, Supine	
							First Measurement	Last Measurement
A. B.	M.	33	5 ft. 7½ in. (1.71 m.)	9 st. 2 lb. (58.1 kg.)	<i>Patients</i> Intercostals and diaphragm. 16/11/49	65 approx.	180 c.cm. 6/12/49	840 c.cm. 15/3/50
M. C.	F.	20	5 ft. 6 in. (1.68 m.)	7 st. 8 lb. (48.1 kg.)	Intercostals and diaphragm. 10/11/49	More than 125	215 c.cm. 11/1/50	
R. J.	M.	17	5 ft. 6 in. (1.68 m.)	7 st. 7 lb. (47.6 kg.)	Intercostals and abdominal wall, not diaphragm.	31	1,100 c.cm. 30/11/49	1,600 c.cm. 26/1/50
D. P.	F.	26	5 ft. 6½ in. (1.69 m.)	8 st. (50.8 kg.)	Intercostals and diaphragm complete. 30/7/49	150 approx.	450 c.cm. 1/12/49	600 c.cm. 15/3/50
D. J. D.	F.	34	5 ft. 2½ in. (1.59 m.)	8 st. (50.8 kg.)	<i>Healthy Subjects</i>		3,200 c.cm.	
E. D. J.	F.	35	5 ft. 9½ in. (1.77 m.)	10 st. 4 lb. (65.3 kg.)			3,000 c.cm.	
F. D. S.	M.	26	5 ft. 7½ in. (1.71 m.)	10 st. 5 lb. (65.8 kg.)			4,400 c.cm.	
L. M. T.	F.	28	5 ft. 4 in. (1.63 m.)	9 st. 5½ lb. (59.6 kg.)			3,100 c.cm.	

The weights given for the patients are those stated by them as observed before their illness. During these studies all patients showed great muscular wasting, with consequent loss of weight.

FIG. 2.—Tidal air and respirator suction pressure in four poliomyelitis patients and four healthy adults. All measurements taken at steady valve settings, some time after any change of conditions. The large dots indicate two coincidental observations. Dotted lines show the calculated regression lines.

stroke rate of 20 a minute, and include 86 tests on the patients with poliomyelitis and 33 on healthy subjects. The points show a wide scatter, and even if those measured in fairly quick succession—that is, at a few minutes' interval—are joined by lines to give curves, these show wide variations in slope, especially in the healthy subjects. The causes of the wide scatter shown in these graphs are only partly known. In the patients, some of the higher values of tidal air were due to an irrepressible desire to be "helpful"—that is, to a voluntary effort added to the effect of the respirator. This was especially marked in R. J.

The healthy subjects practised as complete relaxation as possible. The tests were done at varying times after meals, and one subject (E. D. J.) habitually showed unconscious

resistance to hyperventilation, presumably by contraction of trunk muscles or of the glottis.

Table II shows certain values calculated from the dotted lines in Fig. 2 and from curves similar to those in Fig. 1. Owing to the wide variations found, the figures in Table II should be taken only as a rough guide. The data for R. J. in particular show the effect of movements of the diaphragm, which remained functional. The healthy subjects all show less resistance to the respirator action than do the patients. This may be due to many causes, such as unconscious co-operation of voluntary muscles in the healthy subjects, the development of chest rigidity in the patients, or possibly to resistance of the laryngeal or other muscles against hyperventilation, which might occur in the patients at unusually low volumes of tidal air owing to their wasted condition.

Optimum Pressures for Tank Respirator

It is obvious that the correct suction pressure for respirator patients can be best judged by studies of blood oxygen and of either blood CO_2 or alveolar CO_2 . If reliable measurements of that type are not available, it seems reasonable to assume that, unless fever is high or obstruction by fluid or mucus is present, the normal values of tidal air for healthy subjects should be satisfactory—that is, that for adults lying at rest, with their lungs in a healthy state, the tidal air should not exceed 600 c.cm. and should not be less than 400 c.cm. for a respiration rate of

15 cycles a minute. It should be measured if possible, but if this is impracticable the above data suggest that for adolescents or adults a suction pressure of -12 to -15 cm., according to the freedom of chest movement, is likely to be of the right order, and should be tried as a starting point. This agrees closely with the conclusions of Wilson (1947).

Effect of Positive Pressure on Tank Respirators

In some tests (not quoted above) positive pressures of 9 to 10 cm. H_2O were used with negative pressures of from 10 to 19 cm. Over this range such increase in tidal air as may have occurred with the change from 2 to 10 cm. of positive pressure was too small to be detected in our tests.

TABLE II.—Relation Between Tidal Air and Respirator Pressure

	Patients				Healthy Subjects		
	D. P.	A. B.	M. C.	R. J.			
Negative pressure (cm. H_2O) giving tidal air of 400 c.cm. . .	-16.0	-14	-15.3	No. mechanical aid needed	-7.15		
Ditto for 500 c.cm. . .	-23.5	-21	-20.7	"	-10.0		
C.cm. increase in tidal air for each cm. increase in negative pressure, for "equilibrium" data . .	13.1	14.5	18.2	19.9	35.4		
Ditto for points taken during rapid changes of pressure . .					E. D. J.	D. J. D.	F. D. S.
					19.4 and 17.4	39	51.5 and 64

FIG. 3.—Vital capacity (v.c.) and tidal air (t.a.) with unaided respiration for two convalescent poliomyelitis cases.

This agrees with the results of other workers—for example, Wilson (1947). While suggesting that positive pressures of this order are not of much value in increasing tidal air, these tests do not warrant the conclusion that they are useless, since it seems possible that they help to maintain flexibility of the chest and to assist circulation in the lungs, liver, etc. Such observations as were made tended to confirm the belief that positive pressure at part of each stroke does help patients to cough. Both A. B. and D. P. developed atelectasis at one time, and this aid to coughing was then thought to be of definite value, especially if combined with a tilt of 15 degrees head downwards.

Pressure Selected by Patients

In Fig. 2 the graphs for M.C., A.B., and D.P. all show a concentration of points at about -15 cm. pressure. This represents the smallest suction with which these patients felt comfortable during the later portion of their stay in respirators. In the first weeks M. C. became very uncomfortable at pressures less than -22 cm. (at which her tidal air varied from 250 to 590 c.c.m.). At -16 cm. she felt "unable to breathe from the bottom." Even at -22 cm. (and $+2$ cm.) she showed signs of anoxia at this period. R. J., with a milder extent of paralysis and a relatively flexible chest, also appeared to like -15 cm. pressure, though this gave him a tidal air of over 850 c.c.m. and a minute volume of 13 to 14 litres.

From these four cases it would seem that the patients' desires may be a useful guide to correct respirator pressures in the absence of all measurements of tidal air or of alveolar or blood gases. Owing, however, to the ease with which the respiratory centre becomes adapted to abnormal concentrations of CO_2 , the patient may in time come to prefer a pressure which causes either alkalosis or acidosis (Brown *et al.*, 1948; Elam, 1948).

Effect of Stroke Frequency on Tidal Air

The patients concerned were not well enough to tolerate tests of varying respirator frequency over an extensive range. Tests on three healthy adults showed in each case a gradual fall with increasing frequency, the tidal air at 30 cycles a minute being approximately half that at 12 cycles a minute. In contrast to this Shaw and Drinker

(1929) reported that in anaesthetized cats treated with curare the tidal air was practically identical at 22 and 37 cycles a minute for all pressures from ± 6 to ± 20 cm. H_2O . This difference may be due to narrowing of the bronchi during expiration in our healthy subjects (who reported feeling unable to finish expiration at the higher speeds), or to unconscious resistance to over-ventilation. We think the latter explanation improbable.

All healthy subjects found 20 cycles a minute, which is the minimum frequency of the normal Both respirator, uncomfortably fast. They preferred speeds of 12 to 16 cycles a minute, more nearly resembling those of normal respiration when lying down. We see no reason to think that adult patients without fever need higher frequencies than this in most cases. The obvious advantage of using a relatively low frequency is that it facilitates a

tidal air large enough to make atelectasis unlikely, and gives less risk of hyperventilation. In the presence of active infection other considerations may become dominant and make higher frequencies preferable.

Tidal Air in Patients Removed from Respirators

Measurements of tidal air and vital capacity form a useful aid in judging the rate at which patients can be weaned from respirators. Fig. 3 shows such measurements for two patients who showed both diaphragmatic and intercostal paralysis. In each case the patient was supine either on a bed or on the respirator mattress with the box front open and no pump running.

The lowest curve (for M. C.) is of interest in showing what low values of tidal air can be tolerated in a wasted convalescent patient. By the 63rd day, with a tidal air of 150 c.c.m., she could tolerate periods of 35 minutes without mechanical aids to respiration. At the 125th day she was able to stay out for periods of six hours daily, and showed an unaided tidal air of 350 c.c.m., with an alveolar CO_2 of 5.9%. The two higher curves in Fig. 3 show tidal air and vital capacity for A. B., again when unaided by the respirator. On the 20th day he showed collapse of the lower lobe of the right lung, with a tidal air of 150 to 180 c.c.m. By the 49th day he was out of the respirator all day and night, with a tidal air of 290 c.c.m. A few days later return to the respirator seemed advisable, and he finally left it on the 101st day. On the 119th day he showed the tolerable figures of 460 c.c.m. for tidal air and 850 c.c.m. for vital capacity. He was fortunate in regaining at least partial control of the upper intercostal muscles, although the diaphragm and lower intercostals remained wholly paralysed.

Fig. 4 shows spirometer curves for tidal air and vital capacity tests for one healthy subject (F. D. S.) and three convalescent patients drawn to the same scale. It shows graphically how great the damage to respiratory muscles may be in cases which survive. The reserve air is shown approximately in each case by the depth to which the curve falls below the dotted line. The vital capacities of the patients are so low as to leave little or no margin for emergencies such as an acute respiratory infection.

Posture in Respirators

It is customary in most hospitals to nurse respirator cases in the supine position, tilting the head downwards only when fluid collects in some part of the respiratory tract. While convenient for both nurses and patients, any constant posture is dangerous, and the supine position is exceptionally dangerous owing to the difficulty of draining the pharynx without excessive tilt and the increased danger of inhalation of gastric contents if vomiting occurs. This applies to all cases needing respirators, and especially to bulbar cases whether in respirators or not.

Statistics of deaths from poliomyelitis show that a large majority of respirator patients die—for example 86% of 834 cases (Bergman and Hultdt, 1948), 82% of 98 cases (Edwards, 1948), 57% of 63 cases (Brahdy, 1936), 80% of 76 cases (Nielsen, 1946). Useful data for earlier epidemics are given in the Medical Research Council's Special Report on Breathing Machines (1939). A large number of these patients die with atelectasis and pneumonia, probably accentuated, if not chiefly caused by, accumulation of mucus and fluid in the respiratory tract. While making due allowance for the cases in which death is due to overwhelming invasion of the central nervous system it seems reasonable to suspect that a good many such deaths could be averted if continuous drainage of the main bronchi were assured. Postural drainage is therefore of very great importance in many cases. It is well known as a life-saving measure in bulbar poliomyelitis, but its possibilities during respirator treatment have been little explored.

The great advantage of the prone position over the supine in facilitating drainage is not always appreciated. In the supine position, lying flat on a hard surface, there is an upward slope from the carina to the lower corner of the mouth (with the head turned sideways) of approximately 15 degrees. Hence a downward tilt of over 15 degrees is necessary before drainage can even begin, and about 20 degrees is necessary for a useful effect. (These figures are only approximate, since the exact angle of slope is affected by the shape of the chest, the yield of the mattress, and especially by the position of the head at rest.) The reverse holds in the prone position. With the body lying on a horizontal surface, and with the chin in a comfortable position about $1\frac{1}{2}$ in. (3.75 cm.) below the surface supporting the trunk, there is a downward slope of about 15 degrees from the carina to the mouth, so that rapid drainage can occur without any tilting of the patient. The difference between the prone and the supine position thus corresponds to a tilt of about 30 degrees when considering the respiratory tract from carina to mouth. For drainage of all the bronchi distal to the carina no single position can be satisfactory, and changes of posture are indispensable.

Side-effects of Tilting.—The drawbacks to lying with the head tilted downwards deserve consideration. In our tests, two healthy subjects lying prone in an open Drinker respirator tilted head down at 20 degrees for one hour showed oedema of the face, congestion of the nasal mucosa, and alterations in the pitch of the voice. This suggests that even this moderate angle may cause appreciable cerebral oedema, and provides a further reason for using the prone

FIG. 4.—Vital capacity tests (v.c.) in one healthy subject and in three convalescent respirator patients. R.A. = Reserve air.

position, where a small angle of tilt may suffice. The drastic procedure of tilting to 30 or 35 degrees is, however, advised by Galloway and Seifert (1949), who report successful results in 15 consecutive bulbar cases.

Posture in Both and Drinker Respirators.—These respirators have sloping fronts, which are advantageous to patients when supine, but tend to interfere with the shoulders in the lateral position and with the chin in the prone position. In this respect the Both with the wooden front $\frac{7}{8}$ in. (2.2 cm.) thick, sloping at 20 degrees, is worse than the Drinker with a metal front $\frac{3}{32}$ in. (0.24 cm.) thick, sloping at 15 degrees. However, changes of posture were studied in two patients. The prone position was found practicable for A.B. in a Drinker respirator for periods up to two hours at a time. The left lateral position was also found useful in this patient, following collapse of the right lower lobe, but this position was tolerated only for periods of two hours at a time, since his left hip became tender. A boy of 3 was also nursed in a Drinker for long periods in the right and left lateral positions.

When in the prone position the patient needs one or two pillows under the chest and thighs to allow of free abdominal movement in respiration, and two pillows under the shins to protect the knees and feet from pressure. We have found it easy to construct a chest and shoulder support from one of the wedge-shaped cushions of foam rubber sold commercially for upholstery. The removal of the central part of the thin end of the wedge facilitates abdominal movement, and the addition of two pads of foam rubber projecting above the thick end of the wedge effectively protects the shoulders when the respirator is tilted head downwards.

Effect of Posture on Tidal Air in Respirators.—A series of tests on A. B. at different dates showed no decrease in tidal air on changing from the supine to the prone or lateral positions, at the same respirator pressure. In many tests an increase occurred, but it is uncertain if this was due to conscious or unconscious use of the accessory respiratory muscles or to decreased mechanical resistance. When nursing in the prone or lateral positions no increase in respirator pressures seemed necessary to secure comfort. In two healthy subjects tests showed no regular change in tidal air on changing from the supine to the prone position.

Respirator Mattresses.—In wasted patients the properties of the mattress become of great importance. It is customary to use foam-rubber mattresses in respirators, but these are often covered with a thick waterproof covering of red rubberized fabric. A series of tests made on the yield and elasticity of mattresses (to be published later) have shown that the use of covers of this type greatly increases the local pressure on bony points and removes many of the great advantages of the foam-rubber mattress. The patient A. B. when in the lateral position on a mattress covered in this way soon complained of sore hips. Since "dunlopillo" material is easily washed, and since we are informed by the makers that it can be steamed at 100° C. (but not 110° C.) without appreciable damage, we would strongly advocate the use for all respirator patients of foam-rubber mattresses with thin porous cotton fabric covers only.

Conclusions on Posture.—The advantages of the prone position with slightly lowered head seem to need the greatest emphasis, above all in bulbar cases, whether these are treated out of respirators, as is common in this country, or in them, as strongly recommended by Galloway and Seifert (1949). Improvements in the design of tank respirator fronts to facilitate changes of posture are badly needed. Training of the nursing staff in team-work when changing the posture of respirator patients is also important.

Hyperventilation

The ease with which hyperventilation can be produced in tank respirators was noted by Drinker and Shaw (1929) and should not be forgotten. In healthy subjects considerable hyperventilation can be continued for 24 hours or more as shown by Brown *et al.* (1948), though during sleep some mechanism (possibly closure of the glottis) reduced the ventilation in at least one of their subjects. In this respect tank respirators are in striking contrast to manual methods of artificial respiration in which hyperventilation is usually impossible, owing to an ensuing rigidity of the chest sufficient to overcome its natural elasticity (Henderson and Turner, 1941).

The possible dangers of hyperventilation in respirator cases of poliomyelitis need consideration. They are difficult to assess not merely because the conclusions of workers who have studied hypocapnia vary considerably but also because different persons vary greatly in their response to hyperventilation. Some of these dangers have been described by a number of workers, including the following.

Henderson (1910) and Henderson and Haggard (1918) described some very severe tests on anaesthetized dogs, in which three dogs died. In human beings with less severe hyperventilation Hinshaw, Rushmer, and Boothby (1943) found that in tests in which "the rate and amplitude of respiration were merely doubled" two out of ten aeroplane pilots collapsed in 20 minutes, with partial or total unconsciousness, and four others developed troublesome symptoms. The authors refer to this

as "such moderate hyperventilation," but, since the alveolar CO₂ was in all cases reduced to half the normal figure within five minutes of starting, we infer that the minute volume was four times the normal figure, a rate which we should regard as giving considerable hyperventilation.

Rahn *et al.* (1946) give quantitative data on the effect of hypocapnia on manual steadiness, mental arithmetic, and other faculties, and find a slight drop in efficiency as the alveolar CO₂ pressure falls to 30 mm. Hg and a rapid fall when this pressure sinks below 25 mm., corresponding to a concentration at normal pressures of approximately 3%. (The partial pressure of alveolar CO₂ with normal ventilation is usually taken as 40 mm.)

Carrer (1947) stresses the dangers of respiratory alkalosis and describes it as causing anxiety, confusion, and often a sense of suffocation tending to cause yet further hyperpnoea; sensations of tingling or numbness in the extremities, muscle tetany (especially carpopedal spasm) follow. He attributes some of these symptoms to tissue anoxia. This can be caused by hyperventilation, because the readiness of oxyhaemoglobin to give up oxygen is lessened by a reduction in the CO₂ content of the blood stream. This has long been recognized as the "Bohr" effect.

A further possible cause of tissue anoxia from hyperventilation is suggested by the studies of Gibbs *et al.* (1942), who conclude that a reduction in the arterial CO₂ content of arterial blood causes constriction of the cerebral arterioles. While these authors hold that such constriction will not be sufficient to cause anoxia, others such as Davis and Wallace (1942) believe that at least sufficient anoxia to produce delta waves is easily caused in this way.

The tetany produced by hyperventilation in man has been recorded by many workers, including Grant and Goldman (1920) and Schneider (1930). The latter observed great spasticity of the chest or shoulder muscles in some of his subjects after about 22 minutes of voluntary forced breathing. This seems of possible interest in considering the "rigid chests" of some respirator cases. The effects of hyperventilation during anaesthesia are discussed by Seevers *et al.* (1939, 1940). If hyperventilation is prolonged a rapid adjustment of the blood alkali occurs, tending to restore the pH of the blood to its normal value. The kidneys aid in this process by secreting a more alkaline urine. As a result of these adjustments, overbreathing is not known to cause death in healthy unanaesthetized human beings or dogs. It is, however, uncertain whether hyperventilation in respirators has often proved lethal in the acute stage of poliomyelitis.

Practical Tests on Hyperventilation in Drinker or Both Respirators.—Table III gives the results of a few of our tests on healthy subjects, and is intended to show at what pressures appreciable hyperventilation occurred. In three out of four healthy adults suction pressures of -13 to -16 cm. H₂O at respirator rates of 14 to 20 a minute caused pronounced symptoms of respiratory alkalosis in less than 90 minutes from the start, with a reduction of alveolar CO₂ to less than 3%—that is, to less than 25 mm. Hg pressure. These findings agree well with those of Rahn *et al.* (1946) quoted above.

Hyperventilation in Patients.—With patients the respirator pressures were generally adjusted to the lowest value at which the occupants felt comfortable, and no signs of overventilation were detected. In three of the patients this was only to be expected, since their tidal air was small. With R. J., however, a tidal air of about 800 c.cm. and a minute volume of 16 litres or more was common, as is seen in Fig. 2. Even on the first morning after entry into the respirator a minute volume of 17 litres was observed (at pressures of -17 cm. and +2 cm. H₂O). It seems certain that some hyperventilation occurred, though conceivably only during spirometer measurements. No symptoms or signs of overventilation were detected.

TABLE III.—*Respirator Pressures Causing Hyperventilation in Healthy Subjects*

Subject	Negative Pressure (cm.H ₂ O)	Stroke Frequency	Tidal Air (c.cm.)	Minute Volume (litres)	Duration Since Start of Pump (min.)	Alveolar CO ₂ %	Symptoms of Alkalosis
L. M. T.	-15	19.5	1,000	19.5	0 15 30 40	4.46 2.45 2.25 1.95	Tingling + Chvostek's sign at 12 min. Carpal spasm at 38 min.
L. M. T.	-16	16	900	14.4	0 25 38 50	4.4 3.94 2.74 2.45	Tingling in arm and bilateral Chvostek's sign at 42 min. Carpal spasm at 48 min.
L. M. T.	-13	14-16	900	13.5			Tingling, carpal spasm, and Chvostek's sign at 3 min. Brief loss of consciousness and sweating hands at 45 min.
F. D. S.	-15.5	16	980	15.6	0 16 30	5.5 3.1 3.45	Tingling at 13 min. Chvostek's sign at 23 min.
F. D. S.	-13	20	650	13.0	0 14 34 70 93 124	5.96 4.14 3.85 3.23 2.85 2.95	Tingling at 82 min. Chvostek's sign at 92 min.
D. J. D.	-14	20	600	12.0	0 26 61 83	— 3.44 2.88 2.43	Tingling + Chvostek's sign at 72 min. Trousseau's sign + carpal spasm at 83 min.
E. D. J.	-16	14.5	575	8.2	0 32 69	5.85 4.75 4.1	No symptoms.
E. D. J.	Voluntary hyperventilation		2,066	31.0	19.5	Not measured	No symptoms after 19½ min.

Note: Positive pressures used varied from 0 to 1 cm.H₂O.

Indications for Respirator Treatment

The high percentage of deaths observed in cases of poliomyelitis treated in respirators has led many physicians to postpone respirator treatment until the patient is obviously struggling for breath. Thus Stimson (1949) remarks: "The contraindications to the use of the respirator, however, are so definite that a number of us feel that a patient should not be put in until you really have to." While realizing that the dangers of respirator treatment may be appreciable, especially when there is a shortage of nurses, we would like to emphasize the physiological grounds for thinking it important to use respirators at the earliest detectable signs of involvement of the respiratory motor neurones.

Ritchie Russell (1949) has pointed out the close correlation between muscular paralysis and exercise in the 72 hours preceding the onset of paresis. He remarks: "Severe physical activity at this stage is almost suicidal." This seems to be especially true in the last 24 hours of the pre-paralytic stage. Now the vital capacity of most people is about eight times as great as their tidal air when at rest. Hence a patient at rest will not show distress from failure of respiratory muscles until a very large fraction of their power is lost. It seems probable that by that time many of their neurones are already out of action, and that the remaining ones are being grossly overstimulated by hypercapnia or hypoxia. It therefore seems most important to rest these muscles before this stage is reached. A further reason for prompt respirator treatment is summarized in the well-known adage "Anoxia breeds anoxia." It therefore seems important that respirator treatment should not be postponed until gross signs of underventilation such as cyanosis, difficulty in answering questions, or twitching of the alae nasi have developed.

In the four surviving respirator cases discussed in this paper the procedure customary in most hospitals was followed, in that the patients were kept under close clinical observation but respirator treatment was not begun

until respiratory difficulties were obvious. The time intervals between the first symptoms of respiratory insufficiency and the use of a respirator were as follows: D. P., 26 hours 50 minutes; M. C., 24 hours approximately; R. J., 5 hours 30 minutes; A. B., 4 hours 30 minutes. It is of interest that of these patients the least recovery of respiratory power was shown by D. P. and M. C., who had the longest intervals before respirator treatment. Both these patients died within a year with acute dilatation of the stomach and, in one or both cases, pneumonia.

In determining the first onset of respiratory weakness a rough estimate can be formed by finding how many numbers the patients can count out verbally in one expiration. But if the apparatus is available, some kind of spirometer is much more accurate. In our opinion a spirometer of the type commonly supplied for estimating the basal metabolic rate should be kept as an accessory in every ward where an appreciable number of respirator cases are expected. In the absence of a spirometer of this type, simple apparatus can be constructed for measuring "vital capacity," using either an expanding bellows of paper or cloth, or a metal float chamber as in spirometers. It is even possible to measure vital capacity by using an anaesthetist's rubber bag (the 2-gallon (9.1-litre) size may be needed for adult males), by tying up the orifice and noting the volume of water displaced on immersing the bag in a large vessel. By taking measurements of this sort at suitable intervals it should be possible to detect a weakening of respiratory muscles in the earliest stages, and to justify beginning respirator treatment much sooner than is now customary, at least in hospitals where the staff are fully trained in the management of respirators.

As this conclusion was reached only in the later part of our studies, we have not yet had practical experience of the difficulties which might ensue from this procedure. We do not know if the net result would be to increase or decrease the number of respirators needed, since a shorter period of stay might outweigh an increase in the number

of patients given the treatment. It would of course be important to avoid respirator treatment in bulbar cases, unless they were efficiently drained by tilting or other methods.

Matching of Respirator Frequency to Patient

The normal respiration frequency of an adult lying down is said to be 14 to 16 a minute, falling to about one-quarter of this rate during sleep (Sunderman and Boerner, 1949). All our healthy subjects when first put in a Both respirator found it difficult to adjust to the frequency of 19–20 a minute, which is the lowest that the belt of the A.C. power unit supplied with the Both outfits can give. These subjects felt as if they were not allowed time to breathe out properly, and it was difficult at first to adjust their muscles to the unduly early onset of inspiration. On the other hand, with the D.C. motor of the Drinker outfit, giving speeds down to about 10 strokes a minute, no such difficulty was noticed.

The logical procedure for matching respirator to patient would consist in noting the unaided frequency of the patient's respiration and, when this was not excessive, adjusting the respirator stroke frequency to the same rate. This should give least fatigue to the muscles concerned. It seems important to avoid hyperventilation, since this is normally resisted (at least in healthy subjects) by contraction of respiratory or laryngeal muscles which presumably need rest.

Hypoxia

It seems clear from the observations of Elam *et al.* (1948) that the use of an oximeter may be of great value in the respirator treatment of poliomyelitis. This would make the detection of underventilation easy but would give no guide to hyperventilation. For the detection of this, measurements of alveolar CO_2 would be of great value, and the combined procedure would make it possible to determine the best value of the minute volume for a patient in any particular phase of his illness. In the absence of such facilities it seems wisest to assume that hypoxia is more dangerous than hypocapnia, especially when the latter is of gradual onset so that the acid-base balance can be adjusted by the kidneys. It is therefore reasonable to choose a minute volume rather greater than the optimum theoretical value for a patient at rest. As is well known, many cases require, or at least benefit from, the use of oxygen for a considerable period after treatment has begun. Further, in order to avoid hypoxia when the tank respirator is opened for nursing attention, it is very important to have some auxiliary apparatus available, such as an Oxford inflator or a McKesson or E. & J. resuscitator.

Suggested Alterations to the Both Respirator

Experience has led us to think the following alterations desirable. The first two seem of considerable importance.

1. Provision for running at lower speeds than the present minimum of 20 strokes a minute. We suggest that if, for economic reasons, an A.C. motor and stepped pulley is retained, ratios should be provided giving 12, 15, 18, 21, and 24 cycles a minute. This would make it possible to give patients rather deeper breaths without so much over-ventilation, and would, we think, often make it easier to match the respirator speed to the natural rate of the patient.

2. Alterations to the front of the tank to make the prone or lateral positions less uncomfortable. A reduction of slope to 10 degrees or even less is suggested, and the replacement of the thick wood by light alloy 3/32 in. (0.24 cm.)

FIG. 5.—Correction curves for water manometers at 20 cycles a minute. These curves and those in Fig. 6 show the amount to be added to or subtracted from the observed reading in order to obtain the correct pressure. They were obtained by comparing the water manometers with a critically damped diaphragm type of pressure gauge. B1, B2, B3 = three different Both respirators. D1, D2, D3, D4 = four different Drinker respirators.

thick. If the front were made in an upper and a lower half, with the upper half easily removable, it would be much less difficult to change the patient's posture.*

3. The valve flaps giving control of pressure are at present too easily misplaced or obstructed—for example, by a pillow placed on top of the respirator.

4. The provision of an alarm signal to call attention if undue leakage or other causes produce a cessation of adequate pressure changes.

5. The addition of a metal pressure gauge in addition to the existing water gauge. A note on the errors found in the water gauges of existing Both and Drinker respirators is added as an appendix.

6. The tilting mechanism is unsatisfactory and should be made easier to operate quickly.

7. A series of minor details could be improved: softer sponge-rubber collars, more side openings, castor wheels, and an internal low-temperature heater could make the machine safer for the patient and easier for the nursing staff.

Summary

Numerous measurements of tidal air have been made with a spirometer on patients and on healthy subjects in Both and Drinker respirators, and on patients after respirator treatment for poliomyelitis. These measurements show a wide range of variation from day to day in most cases.

It is considered that in the treatment of poliomyelitis with respiratory involvement there is much need for measurements of

*We have to thank Dr. Ritchie Russell for this suggestion.

FIG. 6.—Correction curves for water manometers at 25 cycles a minute.

vital capacity and tidal air, unless frequent measurements of blood O_2 and CO_2 are practicable.

Early measurements of vital capacity are suggested in order to detect the first signs of respiratory involvement, with a view to resting the muscles concerned by the prompt use of a respirator. The tidal air measurements are indicated as a rough guide to the correct setting of respirator pressures so as to avoid under- or over-ventilation.

The potential dangers of hyperventilation are discussed, and measurements are given showing the ease with which this is produced in respirators.

Tests on the use of the prone position in respirators are described. The importance of using this position is emphasized, especially in bulbar cases.

Some possible improvements in the Both respirator are discussed, in particular provision for slower speeds and a reduction in the angle of slope and in the thickness of the front panel.

We wish to acknowledge our thanks to Dr. Ritchie Russell, who initiated this work and who has given constant advice throughout it, and to Dr. W. Howlett Kelleher, physician-superintendent of the Western Hospital, for allowing us free use of clinical material and facilities in the hospital, and for his continued co-operation.

APPENDIX

Note on Water Manometers in Both and Drinker Respirators

The water manometers normally fitted to the Both and Siebe Gorman Drinker respirators have the great merit of simplicity; they may, however, give very misleading readings because of (a) zero error caused by evaporation of the water; (b) over-swing due to the momentum of the water column, causing too high readings; and (c) overdamping by viscosity, causing too low readings. Of these (a) is not serious provided the level is adjusted at regular intervals; (b) and (c) may compensate each other to a considerable extent, but as these two effects depend on both the amplitude and the frequency of the motion of the water column they cannot generally be made to cancel each other at all pressures and rates.

Figs. 5 and 6 show correction curves plotted for seven different respirators. In two of the Boths, the cancellation of errors (b) and (c) above is good, but the remaining Both, reading low by about 40%, demonstrates one of the special dangers inherent in the design of the pressure gauge; this large error was apparently due to an accumulation of foreign matter in the manometer and shows the need for a drainage plug at the bottom of all water manometers on respirators. The existing Both gauge cannot be cleaned out without unscrewing it from the respirator, which has to be done from the inside. The Drinker gauges show clearly the variation of the error with different rates and pressures. As gauges differ in diameter, these errors vary considerably from one gauge to another.

Since it does not seem possible to eliminate these errors over the whole range of pressures and rates required, the provision of an additional dial-type gauge has much to recommend it. A pressure gauge of this type can be made critically damped and still rapid enough in response to give true readings at the highest rates and pressures ever required. It has the advantage that it provides an indication of the correct functioning of the respirator which is visible from a much greater distance than the water manometer.

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Before the last war the General Nursing Council for England and Wales required candidates for entry into the nursing profession to hold certain minimum standard qualifications. Among these was the passing of the school certificate or matriculation examination. Since these are soon to be replaced by the general certificate of education, the G.N.C. has discussed what subjects of this certificate will be acceptable and what the minimum standard should be. It has decided that, when it can once again require a minimum standard of education for entry into the nursing profession, it will accept a pass at ordinary level in two of the following subjects, of which one must be English language or English literature: English language, English literature, history, geography, and religious knowledge. The G.N.C. cannot at present require these qualifications.