AN EXPERIMENTAL STUDY OF DIFFERENT METHODS OF ARTIFICIAL RESPIRATION

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Two articles have appeared recently (Cordier, 1943; Eve, 1943) in which the criteria of efficiency of different methods of artificial respiration have been discussed. The aim of all methods of artificial respiration is agreed upon—it is the maintenance of respiratory exchanges in the nervous system. For this to take place two fundamental requirements must be fulfilled: (a) adequate pulmonary ventilation; (b) transport of respiratory gases from and to the lungs. Cordier devotes attention to the first of these fundamentals, while admitting the importance of the other, and reviews the experimental evidence for the claims of efficiency made for Schäfer's, Silvester's, and the rocking (Eve's) method. He concludes, basing his judgment on lung-ventilation measurements, that the rocking method is not necessarily superior to other methods despite the claims which have been made for it. Eve reiterates the claim (Killick and Eve, 1933) that lung ventilation with the rocking method is equal to that with Schäfer's when measured in a normal subject voluntarily suspending respiration. It is also argued, chiefly on theoretical grounds, that the rocking method is likely to have a more beneficial effect on the circulation than Schäfer's method would have. Both authors, however, stress the necessity for further investigation into the effects of artificial respiration on the circulatory system and the transport of oxygen. Such investigations were actually in progress at the time of publication of those articles, and a preliminary account of them is given in the present paper.

It has been assumed that the fundamental fact to be considered in assessing the value of methods of artificial respiration is the amount of O_2 which can be transported to and used by the tissues. Accordingly, the rates of O_2 uptake, tidal air, ventilation volume, arterial blood pressure, and cardiac output have been measured with different methods of artificial respiration.

The Animal Preparation

One of the greatest obstacles to the experimental investigation of methods of artificial respiration is the lack of a suitable experimental subject. Because methods of artificial respiration are usually required for their application to man, the human subject is the most desirable. But the use of an individual voluntarily suspending his respiration, or rendered apnoeic by voluntary hyperpnoea, is attended by many objections, which have been discussed by Haldane and Priestley (1935), Henderson and Turner (1941), and Cordier (1943), amongst others. The rigidity of the ordinary cadaver makes it an unsuitable subject, and it is easier to suggest the employment of the warm non-rigid cadaver of a previously healthy individual than to undertake it; nor is it possible to investigate circulatory conditions in these circumstances. Anaesthesia carried to the point of depressing the activity of the respiratory and vasomotor centres would appear to give an ideal condition for experiment, and Waters and Bennett (1936) and Macintosh (1943a) have recently described a near approach to it in experiments in which anaesthetized persons were rendered apnoeic, by forced ventilation, for a sufficiently long period to allow tidal air volumes to be measured under different methods of artificial respiration.

Since there did not appear to be any methods by which a suitable human subject could be employed for periods long enough to enable extensive measurements to be made on the cardiovascular system, it was decided to use dogs, either with a spinal transection made between the first and second cervical segments, or deeply anaesthetized with nembutal so that the medullary centres were inactive. For the latter preparation nembutal (1% solution in isotonic saline) was injected intraperitoneally until respiration ceased and arterial blood pressure fell to 50–60 mm. Hg. In either case artificial respiration was maintained by a pump except when manual methods were being investigated. Preparations of this type can be kept in good condition over long periods by artificial respiration, and it is considered that they offer good opportunities for comparing the efficacy of different methods of artificial respiration. The medullary centres are inactive and muscle tone is low.

Measurement of Tidal Air and Rate of O_2 Uptake

Rates of O_2 uptake and volumes of tidal air were obtained by a recording spirometer. A Y-shaped cannula was tied into the trachea and a positive-pressure artificial respiration pump could be switched in or out of the spirometer circuit by a system of taps.

Methods of Artificial Respiration Employed

(a) *Pump Respiration*.—This was instituted immediately before making the spinal section or inducing deep anaesthesia, and the pump stroke was adjusted to give what appeared to be the normal ventilation volume, except when experimental procedures were being undertaken. The usual rate of the pump was 10.8 strokes a minute.

(b) *Abdominal Pressure Respiration (Schäfer)*.—The deep thorax of the average dog makes it an unsuitable subject for "prone-pressure" artificial respiration in the orthodox fashion; the prone pressure was unsuitable also for some of the experimental procedures undertaken. But with the dog supine, very firm pressure can be effectively applied to the abdomen and the viscera driven towards the thorax. It is considered that supine-pressure artificial respiration applied in this fashion is quite effective by comparison with prone-pressure respiration, and was abandoned (Schäfer, 1907–8) largely because of the danger of injury to the liver.

(c) *Rocking Method of Artificial Respiration*.—The animal was firmly strapped to a board by its limbs and stops were placed above and below the shoulders to prevent sliding. Rocking was carried out symmetrically about a horizontal axis through the centre of the board. The angle of rock was measured from the horizontal. A rate of 8 to 10 respirations a minute was usually maintained. So far as was possible the movement was made with a constant velocity, and stopping and starting was done fairly abruptly.

Measurement of Arterial Blood Pressure

Arterial blood pressure was recorded from the carotid or femoral artery. Changes of pressure in the recording system due to alteration of the position of the cannula when rocking was instituted were avoided by using a compensating device.

Measurement of Cardiac Output

Application of the Fick Principle.—Cardiac output was calculated from the formula:

$$\text{Cardiac output (ml./min.)} = \frac{O_2 \text{ uptake (ml./min.)}}{\text{Arteriovenous } O_2 \text{ diff. (ml./100 ml.)}} \times 100$$

The arteriovenous O_2 difference was obtained from analysis of blood samples obtained by arterial and right ventricular puncture. Analyses were made in the van Slyke manometric apparatus. Right ventricular puncture was abandoned after a few experiments because of the technical difficulties during rocking, and subsequently samples of mixed venous blood were obtained by a catheter introduced through

the external jugular vein into the right atrium. Recently a photo-electric cell device, operated on the principle of Kramer (1935) and Pappenheimer (1941), has been used for the estimation of the arterio-venous O_2 difference. It has the advantage that 2-3 ml. of blood is withdrawn only temporarily from the circulation and long series of estimations can be made.

Observations

Effect of Spinal Section on Rate of O_2 Usage.—After spinal section or the induction of deep anaesthesia the rate of O_2 uptake was usually reduced by 25-30%, and the arterial blood pressure had fallen to 40-50 mm. Hg when measurements were made 30-40 minutes later. These points are illustrated by Fig. 1.

FIG. 1.—Rates of oxygen uptake and arterial blood pressure in an animal before and after spinal section.
●—●—● Natural respiration. ○—○—○ Pump respiration (figures under points indicate volume (ml.) of tidal air).
○—○—○ Arterial blood pressure.

Relative Volumes of Tidal Air with Different Methods of Artificial Respiration.—Using the pump for artificial respiration the tidal air volume is determined, within wide limits, by the stroke of the pump and need not be further discussed. When the Schäfer and rocking methods are compared the tidal volume is usually smaller with the former than with the latter. A typical result from some preliminary experiments performed with spinal cats was: tidal air volume with Schäfer's method, 16 ml.; with rocking, 24 ml. In a longer and more satisfactory series of experiments on spinal or deeply anaesthetized dogs a similar relation has been found in the large majority of experiments. In 10 out of 11 experiments the rocking method has given the greater volume of tidal air, and, taking the mean of all the experiments, the tidal air with this method has been 54% greater than with Schäfer's. The difference between the tidal air in the two methods has been greatest when deep anaesthesia has been induced. In these circumstances muscle tone has been very low, and the forces responsible for restoring the volume of the thoracic cavity following the expiratory phase of the Schäfer have presumably been weak: the tidal air has often diminished progressively during the period of artificial respiration despite efforts to increase the expiratory pressure. Low muscular tone is not so likely to affect the volume of tidal air in the rocking method, because the diaphragmatic movements in both the inspiratory and the expiratory phases are impelled by the movements of the abdominal viscera. In this respect the experiments give support to the argument advanced by Gibbens (1942).

Comparison of Rate of O_2 Uptake with Different Methods of Artificial Respiration.—The usual course of an experiment was first to record the rate of O_2 uptake with pump respiration. This was done during two or three periods, and pump respiration was then replaced by either rocking or Schäfer's method of artificial respiration. When the necessary observations had been made pump respiration was reinstituted, and after this the alternative method of artificial respiration was applied. In suitable preparations the whole procedure could be repeated. The results of a typical experiment are depicted in Fig. 2. The rate of O_2 uptake with pump respiration was 23.27 ml./min.; artificial respiration by rocking gave an uptake of 26.6 ml./min., and with Schäfer, 16.8 ml./min.

FIG. 2.—Rates of oxygen uptake. Comparison of artificial respiration carried out by pump, rocking, and Schäfer's method.

In some experiments the rate of O_2 uptake with Schäfer's and the rocking method has been smaller than with pump respiration, as is shown in Fig. 3, but on only one occasion has the O_2 uptake with Schäfer's method been greater than it was with rocking, although often there has been very little difference between them.

FIG. 3.—Similar experiment to that of Fig. 2, but showing gradual fall in oxygen uptake with pump respiration throughout experiment.

The Significance of Tidal Air Measurements in comparing the Efficacy of Methods of Artificial Respiration.—Cordier (1943) observes that "the determination of ventilation is only one criterion in judging the efficiency of these methods." Observations of the type given in Table I show clearly that tidal air is not necessarily the determining factor in O_2 uptake, for with very different tidal airs and ventilation volumes there may be similar rates of O_2 uptake. For in this experiment, although tidal air volumes and ventilation volumes by the Schäfer method were only about 50% of those with the rocking method, there was little difference in the rate of O_2 uptake.

TABLE I.—Tidal Air, Ventilation Volume, and O_2 Uptake

Period	Type of A.R.	Tidal Air (ml.)	Rate per min.	Vent. Volume (ml./min.)	O_2 Uptake (ml./min.)
1	Rocking	125	10.0	1,250	54.0
2	Schäfer	62	10.0	620	50.0
			40-minute interval		
3	Rocking	125	7.6	950	43.0
4	Schäfer	58	10.0	580	43.3

Unless the alveolar O_2 tension is allowed to fall so low that anoxic anoxia supervenes, alterations in the supply of oxygen by changing the tidal air and ventilation volume should not affect the rate of O_2 uptake. That this principle can be applied to the spinal preparation under pump respiration is shown by Fig. 4.

FIG. 4.—Rates of oxygen uptake with alterations in volume of tidal air in animal after spinal section. Figures under points indicate tidal air volumes (ml.).

In this experiment alterations in the volume of tidal air between 100 and 250 ml. had no effect on the rate of O_2 uptake, which fell steadily throughout the experiment. But if, in similar experiments, the tidal air was reduced below a certain volume the rate of O_2 uptake fluctuated with it, as is shown in Fig. 5. Rates of O_2 uptake were measured before spinal section at three different volumes of tidal air, and varied according to the tidal air volume. After spinal section a similar relationship held although the rate of O_2 uptake was lower, and a tidal air of 100 ml. was presumably sufficient to maintain an adequate alveolar O_2 tension.

But it has been observed, in some experiments, that alterations in the volume of tidal air, induced by changing the method of artificial respiration, have been followed by disproportionate changes in the rate of O_2 uptake. The results of such an experiment are given in Table II.

TABLE II.—Tidal Air, Ventilation Volume, and O₂ Uptake

Period	Type of A.R.	Tidal Air (ml.)	Rate per min.	Vent. Volume (ml./min.)	O ₂ Uptake (ml./min.)
1	Pump	100	10.8	1,080	23.5
2	Rocking	94	8.4	789	26.6
3	Pump	100	10.8	1,080	23.2
4	Schäfer	73	10.0	730	16.8
5	Pump	100	10.8	1,080	25.8

The agreement between the rates of O₂ uptake during the periods of pump respiration suggests that the condition of the preparation was fairly stable, but respiration by rocking, although resulting in a slightly smaller volume of tidal air than with pump respiration, gave a higher rate of O₂ uptake. During respiration by Schäfer's method the volume of tidal air was reduced to approximately 78% of that with rocking, but the rate of oxygen uptake fell to 63%.

FIG. 5.—Similar experiment to that of Fig. 4, but showing changes in rate of oxygen uptake according to tidal air volume before and after spinal section.

It was clear from the results of this and similar experiments that, if the effectiveness of artificial respiration methods was to be assessed in terms of the rate of O₂ uptake, factors additional to tidal air volume had to be considered. Some experiments seemed to show clearly that the O₂ uptake varied with the tidal air; others, such as those shown in Tables I and II, pointed equally clearly to the intervention of other factors. Of these probably the most important is cardiac output, and both Henderson (1937) and Schäfer (1903) make reference to it without, however, quoting any experimental evidence. Another section of this work deals with measurements of cardiac output under different conditions of artificial respiration and with the significance of the findings.

Effect of the Angle of Rocking on the Volume of Tidal Air.—Although the volume of the tidal air should not be taken as the sole criterion of the efficacy of a method of artificial respiration, it is necessary to know how the angle of rocking affects the tidal air volume if recommendations are to be made regarding the optimum rate and angle of rocking. Killick and Eve (1933) showed that rocking to 50° in each direction gave a larger tidal air volume in a human subject voluntarily suspending respiration than rocking to 30°, and Macintosh (1943b) has recently made similar observations on an anaesthetized human subject rendered apnoeic by hyperventilation. In a dog, with respiratory activity suspended by deep barbiturate anaesthesia, the results of rocking to various angles were as shown in Table III.

TABLE III

Angle of Rock	Tidal Air (ml.)
30°	108
45°	156
55°	162

Rate of rocking, 9.5 per min.

Apparently, in the dog, the volume of tidal air is not increased significantly by rocking beyond 45° (see also Fig. 6), and since in the human subject rocking to this angle gives a tidal air similar to that in quiet respiration, it appears to be adequate for artificial respiration.

Rate and Rhythm of Rocking: (i) **Rate of Rocking.**—The effect on the tidal air and ventilation volume of rocking at various rates was determined. The results of a typical experiment were as given in Table IV.

TABLE IV

Rate of Rocking per min.	Tidal Air (ml.)	Ventilation Volume (ml./min.)
6.75	146	985
9.50	148	1,405
12.40	144	1,787
16.10	144	2,320

Angle of rock, 45°

The findings are not entirely in accordance with those of Killick and Eve (1933) on the human subject, for they reported that, although there was an increase in ventilation volume as the rate of rocking increased, the tidal volume diminished; in the experiments on the dog the tidal air volume is practically unchanged over the range of rates of rocking investigated. It seemed likely, having regard to the large ventilation volumes ensuing with high rates of rocking, that CO₂ might be "washed out" and the normal stimulus to breathing so removed. In a dog, lightly anaesthetized, it was found that a period of hyperventilation, either with a pump or by rocking, was followed by apnoea. The results of an experiment are given in Table V.

TABLE V.—Effect of Rate of Rocking on Ventilation Volume and Induction of Apnoea

Period	Type of A.R.	Rate per min.	Tidal Air (ml.)	Vent. Vol. (ml./min.)	Duration of A.R.	Duration of Apnoea (sec.)	Rate of O ₂ Uptake (ml./min.)
1	Natural	8.25	146	1,203	—	—	82.0
2	Pump	39.00	200	7,800	125	87	—
3	Rocking	9.50	145	1,378	163	0	79.0
4	"	12.40	156	1,935	135	20	82.6
5	"	16.10	166-146	2,510	145	27	86.7

From the preceding considerations it is obvious that the ventilation volume while rocking should not exceed the normal resting volume if the danger of apnoea is to be avoided; with the human subject, if the usual volume of tidal air in the rocking method is taken as 500-600 ml., the rate should not exceed 10 a minute.

(ii) **Rhythm of Rocking.**—The rhythm of rocking—i.e., the ratio between the duration of the inspiratory and expiratory phases—does not appear to be important in considering ventilation volume provided each is long enough to allow entry or exit of an adequate volume of air. The point will be discussed further, however, in connexion with the circulatory effects.

Effects of Artificial Respiration on Cardiac Output.—The object of any method of artificial respiration should be to maintain or increase the flow of well-oxygenated blood, at a suitable CO₂ tension, through the tissues of the body and, in particular, the brain. Although there is evidence of some vasomotor control of the cerebral vessels in the conscious or the lightly anaesthetized animal (Forbes and Cobb, 1938) it is likely in such cases, and almost certain when the respiratory and vasomotor centres have failed, that the cerebral flow is governed chiefly by the systemic blood pressure and, *ceteris paribus*, this will be determined by the cardiac output. The results of a typical experiment in which the effects on the cardiac output of artificial respiration by positive-pressure pump, rocking, and Schäfer's method, respectively, were compared are given in Table VI.

TABLE VI

Period	Type of A.R.	Tidal Air (ml.)	O ₂ Uptake (ml./min.)	Blood O ₂ (ml./100 ml.)			Cardiac Output (ml./min.)
				Art.	Ven.	Arterio-ven. Diff.	
1	Pump	150	61.1	—	—	—	—
2	"	150	63.3	17.3	12.1	5.2	1,219
3	Rocking	104	60.9	16.7	11.7	5.0	1,218
4	Schäfer	75	53.8	16.7	11.2	5.5	979
5	Pump	150	56.4	—	—	—	—

In three successive experiments of this type the cardiac output with rocking was greater than with Schäfer's method, however vigorously the latter was applied (in one experiment post-mortem examination showed that the liver had been ruptured!); but the changes in cardiac output should not be considered alone but in conjunction with the accompanying alterations in the saturation of the venous blood. This was highest during rocking and lowest during the application of Schäfer's method. In general, the cardiac output, measured during relatively short periods of artificial respiration (5-10 min.) to give accuracy in comparison, has been about 25% greater with rocking than with the abdominal-pressure method.

Having established the superiority, under the given experimental conditions, of the rocking method in its effect on cardiac output, further inquiry was made into the effect of prolonged rocking, and of rocking to various angles. The results of an experiment are represented in Fig. 6. Measurements for the assessment of cardiac output were first made during a period when the animal was under light nembutal anaesthesia. The anaesthesia was then deepened until the respiratory centre was completely depressed, and artificial respiration by the pump was instituted. During this stage the cardiac output was reduced to less than half of what it had been previously under light anaesthesia. Rocking was then started and maintained for 52 minutes, and the cardiac output compared at angles of rock of 30°, 45°, and 55°. Taking the output when the rocking angle was 45° as a standard for comparison, it is clear that the cardiac output increased steadily during the period; but the final response,

when rocking to 55°, indicates that the maximum output had been almost reached. It is important to notice, in assessing the effectiveness of the artificial respiration, that the output at the end of the rocking period and immediately before returning to pump respiration was only 17% less than during light anaesthesia. The rapid decline in the cardiac output to below the pre-rocking level when pump ventilation was restored shows that the increase in cardiac output was due solely to the rocking. The impossibility of assessing the effectiveness of artificial respiration solely by measurement of tidal air volume is also illustrated; for although, with one exception, the volume when rocking was less than the stroke of the pump, the cardiac output was almost double that with pump respiration.

Fig. 6.—Effect on cardiac output of prolonged rocking and of rocking to various angles. Rocking to 30°, 45°, 55° for the periods indicated on the graph. Figures under points indicate tidal air volumes (ml.).

The percentage oxygen saturation of the mixed venous blood immediately before rocking was 46; at the end of the rocking period it had risen to 73, but 30 minutes after the cessation of rocking it had fallen to 53. Referred to a typical O_2 dissociation curve for dog blood at 40 mm. Hg CO_2 tension (E. Neil), these percentage saturations are found to correspond to oxygen tensions of 28.5, 47, and 32 mm. Hg respectively, and the effect of an increased cardiac output in providing a higher unloading tension of oxygen is demonstrated.

Discussion of the Effects of Artificial Respiration on the Circulation and of the Rhythm of Rocking for Maximal Cardiac Output

Only brief consideration can be given to the ways in which the methods of artificial respiration examined—Schäfer, rocking, and pump—affect the circulation. In each case the movements of the body wall and the diaphragm are passive; they are not due to muscular activity. In Schäfer's method the abdominal cavity and contents are alternately compressed and released. During compression the venous return is augmented by the emptying of the splanchnic vessels, but the entry of more blood into the abdominal veins is prevented by the rise in intra-abdominal pressure. When the compression is released and the intra-abdominal pressure falls the splanchnic vessels will fill again and tend to reduce the venous return. Blood-pressure tracings show an increase in mean pressure and a slight increase in pulse pressure during compression; the mean pressure falls abruptly by 10–15 mm. Hg when the compression is released and the pulse pressure is diminished.

During rocking when the head-down position is assumed, there is emptying of the abdominal and hind leg veins by gravity. The diaphragm moves towards the thorax and the intra-abdominal pressure is diminished. There is no impediment to the flow of blood into the abdominal veins. Arterial blood-pressure tracings show a gradual rise in the mean pressure and an increase in the pulse pressure. When the animal is placed in the head-up position blood tends to accumulate in the abdominal and leg veins, although this may be opposed to some extent by the increase in abdominal pressure as the diaphragm descends. Judging by the pulse pressure, the increase in cardiac output in the head-down position is much greater than in the compression phase of Schäfer, and the *vis a tergo* continues to maintain the venous return during the head-up phase.

The accumulation of blood in the abdominal vessels is likely to be minimal if the duration of the head-up phase is as short as is compatible with the intake of an adequate volume of air into the lungs. According to the findings presented in Table V this can be less than 2 seconds without reduction in

the volume of tidal air. Experimentally, a 6-second respiratory cycle, divided into 4 seconds head-down and 2 seconds head-up, has given good results, although a ratio of 3/2 seems slightly better. If the findings are to be applied to the human subject, a 7-second cycle—4 head-down, 3 head-up—might be most suitable, taking into consideration the dimensions and inertia of the stretcher and subject, although Killick and Eve's (1933) results show that a tidal air of 500 ml. can be obtained at 13 rocks a minute.

Comparison of the effects on cardiac output of pump respiration with those of rocking or Schäfer's method provides no consistent conclusions. In some experiments, as in that yielding the results for Table VI, pump ventilation has been as effective as rocking in maintaining the cardiac output; in others—e.g., Fig. 6—the pump has been relatively ineffective in this respect. The explanation of these discrepancies is likely to be complex. Factors to be considered are the effects of lung inflation and collapse on the pulmonary circulation (Daly, 1930) and the extent and effects of diaphragmatic movement in different animals; but since they do not affect the comparison of the two manual methods they will not, at present, be considered further.

Commentary and Conclusions

It is clear from the results of the experiments which have been described that the oxygen uptake and effective transport during artificial respiration is not governed only by tidal air and ventilation volume. It is therefore impossible to assess the efficiency of different methods of artificial respiration by measurement of tidal air volumes if these differ by only small amounts. It is obvious that more attention should be devoted to an assessment of the circulatory changes which are induced by artificial respiration.

It is concluded that the rate of oxygen uptake and the cardiac output are usually greater with the rocking method than with the Schäfer; the O_2 tension of the venous blood is higher.

The reasons for the differences in oxygen uptake with different methods of artificial respiration are not completely clarified. In any one case it would seem to be necessary to consider the following points: (a) Alterations in the tone of muscles due to stretch reflexes which would entail increased oxygen consumption. (b) If tissues are anoxic then increased oxygen supply to the part concerned might be followed by an increased uptake. (c) The higher rate of oxygen uptake with the rocking method than with Schäfer's method may be due, in part, to the increased cardiac output.

The heart rate in the spinal or deeply anaesthetized animal is constant, and alterations in heart output must be due to changes in stroke volume. In experiments employing the cardiometer, an increase in diastolic volume with rocking has been seen, and this will be associated with an increase in the rate of oxygen usage of the heart (Hemingway and Fee, 1927).

Finally, we are in full agreement with the view (*First Aid in the Royal Navy*, 1943) that the Schäfer method should be immediately instituted when resuscitation is undertaken, and that no time should be lost while preparations are being made for the use of any other method.

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