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AN APPARATUS FOR THE PROLONGED ADMINISTRATION OF ARTIFICIAL RESPIRATION

II. A Design for Small Children and Infants with an Appliance for the Administration of Oxygen and Carbon Dioxide

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The apparatus herein described is similar in principle to that designed by Philip Drinker and Shaw (1), but with modifications which will more adequately meet the special requirements of infants and children up to twenty pounds in weight. Though this apparatus has not as yet been available for clinical purposes, the authors believe that its efficacy has been assured both by the tests made with the apparatus already described (1), (2) and by the laboratory tests upon curarized cats in the respirator described in this paper.

A few words will suffice to restate the principle upon which this apparatus operates. The child is placed in a metal box or respirator which has a hole at one end through which the head protrudes and is sealed off by a rubber dam about the neck. After the respirator has been closed, the body is then in an air-tight container with the head exposed to room air. By means of an electrically driven air pump and valve arrangement connected to the respirator, alternate negative and positive pressures may be induced. A negative pressure causes the chest to expand and air will flow into the lungs, while a positive pressure will compress the chest and cause the air to be expelled. Thus a movement of the chest is induced which simulates the natural respiratory movements.

CONSTRUCTION OF RESPIRATOR

The respirator is constructed of metal sheets about 3 mm. thick, soldered or welded together. The whole top is hinged from the side to form the lid and consists of a metal frame in which a heavy plate-

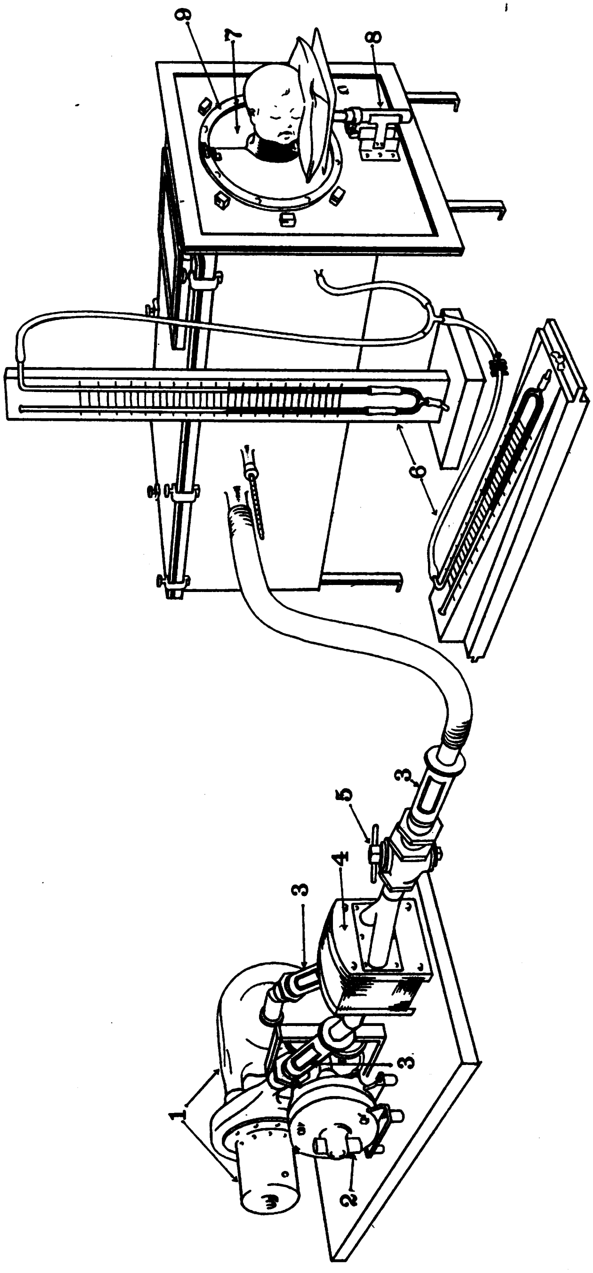

FIG. 1. THE RESPIRATOR AND PUMP

1, pumps; *2*, motor; *3*, vents; *4*, alternate; *5*, valve; *6*, manometers; *7*, external shutters; *8*, adjustment for head rest; *9*, adjustable ring to hold collar in place.

glass window is set in order that the body of the patient may be kept under observation. The lid closes against a rubber gasket and is held fast by means of clamps which, when tightened, render the respirator proof against leaks.

The head passes through a sheet of rubber with a hole in the center. This is made in a mould in such a manner that the edge is reflected to form a collar which fits snugly to the neck (fig. 1). This collar is made in various sizes, the rubber being thin enough to offer no discomfort. As the periphery of the collar is reached the thickness of

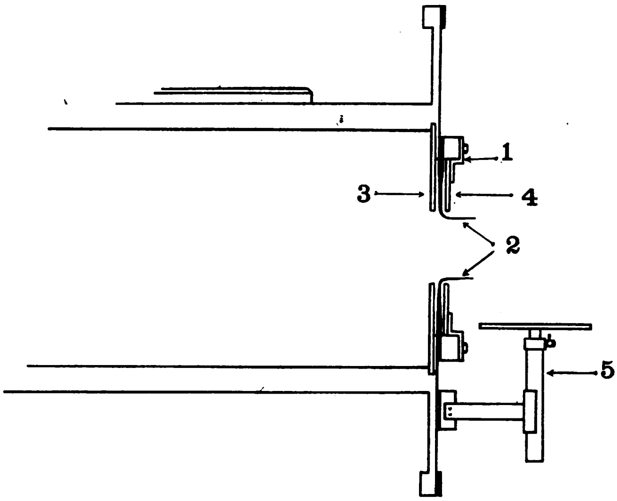

FIG. 2. SAGITTAL SECTION OF RESPIRATOR

1, adjustable ring to hold collar in place; *2*, rubber collar; *3*, internal shutters. *4*, external shutters; *5*, adjustment for head rest.

the rubber is increased slightly, thus giving it sufficient body to act as a gasket when pressed against the ring (fig. 2) about the head aperture.

Having selected the appropriate collar, the neck opening must then be stretched sufficiently to permit the head to pass through comfortably. This is effected by hand or by means of six hook-shaped metal bands which act as retractors. When retractors are used the hooked ends are inserted in the opening of the collar and then drawn back and fastened in place, thus leaving an opening sufficient for the passage of the head through the collar. The hooks are then removed and the collar allowed to close in about the neck. The entire procedure of adjusting the patient in the respirator for the administration of artificial respiration consumes less than one minute.

In order to prevent the thin rubber collar from bulging under the air pressures in the respirator and thus causing both discomfort and leaks, it is necessary to give it support. This is accomplished by two pairs of shutters which are cut out in such a manner that they fit the neck, and when closed, one pair on either side of the collar, the latter is so closely confined that movement is impossible.

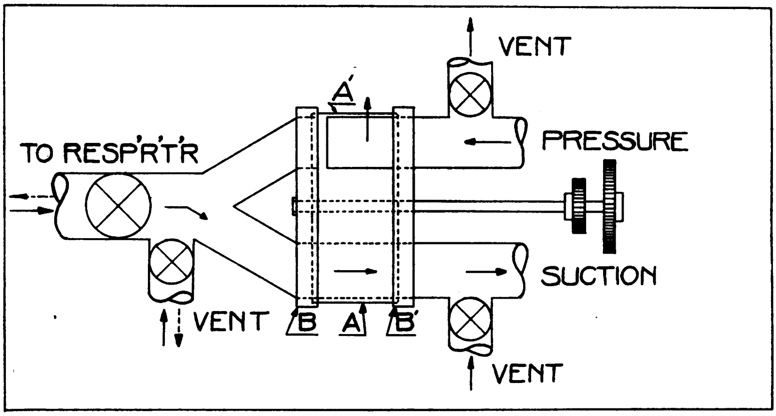

FIG. 3. THE PUMP AND ALTERNATOR

The head-rest may be adjusted for any height. It may also be swung upon a basal pivot into a horizontal position so that it does not constitute an interference while the dam is being adjusted about the neck.

The pressures are created by one or two vacuum cleaners of the ordinary household type. If this unit is too noisy, a small "Roots" blower may be substituted. In either case, a single unit will do the work, although two units should be available in case one fails.[1]

[1] We have found that the double or "twin" unit made by the Electric Blower Co., 352 Atlantic Ave., Boston, answers our requirements. The "Roots" blower is made by the P. H. & F. M. Roots Co., Connersville, Ind.

The approximate mechanical requirements are that the unit shall deliver about 25 cubic feet of air per minute (0.7 cubic meters) at approximately 15 inches (38 cm.) of water pressure. This specification is easily met by several makes of household vacuum cleaners, all of them relatively cheap and easily obtained.

The air pump is connected to the alternator at the points marked *pressure* and *suction* in figure 3.

A valve arrangement is necessary to give alternate positive and negative pressure within the respirator. This valve, called the *alternator*, is shown in figure 3 as parts A, B, and B.′ The bearings are parts B and B′ and are stationary. Part A is rotated by the shaft and gears (shown on the right) at any desired rate from 10 to 50 per minute.

When the alternator is in the position shown in figure 3, air is drawn from the respirator and follows the direction of the arrow down the lower half of the Y-tube, through the alternator to the source of suction. The discharge side of the pump blows air back through the upper half of the alternator (*pressure* connection) and follows the arrow up and out through part A′. When the alternator is rotated 180°, the reverse takes place, viz., air is drawn from the outside air through the bottom of the alternator at A, passes through the pumps, and is blown back through the upper half of the Y-tube and thence into the respirator.

The outlets, indicated as *vents*, are helpful in controlling the pressures applied to the respirator. By opening the *pressure* vent and closing the *suction* vent, the respirator is kept alternately under negative and then atmospheric pressure. By opening the suction and closing the pressure vent, alternate positive and atmospheric pressures are obtained. By closing both pressure and suction vents, alternate positive and negative pressures are obtained.

The vent on the Y-tube (left) side may be placed either as shown or on the respirator itself. It permits by-passing of some of the air to or from the respirator and thus controls the magnitude of the pressure variations. The valve on the main pipe serves the same purpose. We find it convenient to have both valve and vent.

A water manometer connected to the respirator records the pressures while the pump is in action. A second water manometer, also connected to the respirator, but inclined at such an angle that the excursion of the water column is increased ten-fold, is used when the pump is shut off, to detect the presence of respiratory movements. Under these conditions the respirator acts as a plethysmograph in which the changes in volume due to the movement of the chest may be recorded in terms of pressure changes.

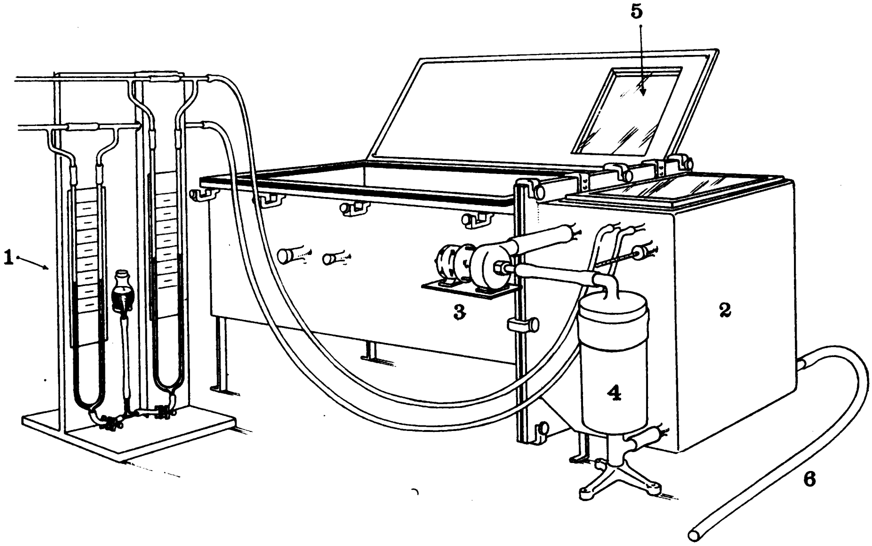

FIG. 4. THE RESPIRATOR USED FOR THE ADMINISTRATION OF CARBON DIOXIDE AND OXYGEN THERAPY

1, flow meters; *2*, gas hood; *3*, impeller blower (Collins type); *4*, soda-lime can; *5*, window; *6*, tube for escape of gas flow.

THE ADMINISTRATION OF CARBON DIOXIDE AND OXYGEN

When it is desired that the patient should breathe an atmosphere enriched with oxygen or carbon dioxide, the head may be inclosed in a chamber or hood (fig. 4) and a mixture of air and oxygen allowed to flow through. The hood has a glass top to permit observation of the head of the patient. It is clamped against the end of the respirator with a rubber gasket intervening to render the compartment airtight. Air and oxygen may be admitted to the hood through flow meters which control the rate of flow. There is a rubber tube of 2 cm. bore and 75 cm. long attached to the hood, the purpose of which is

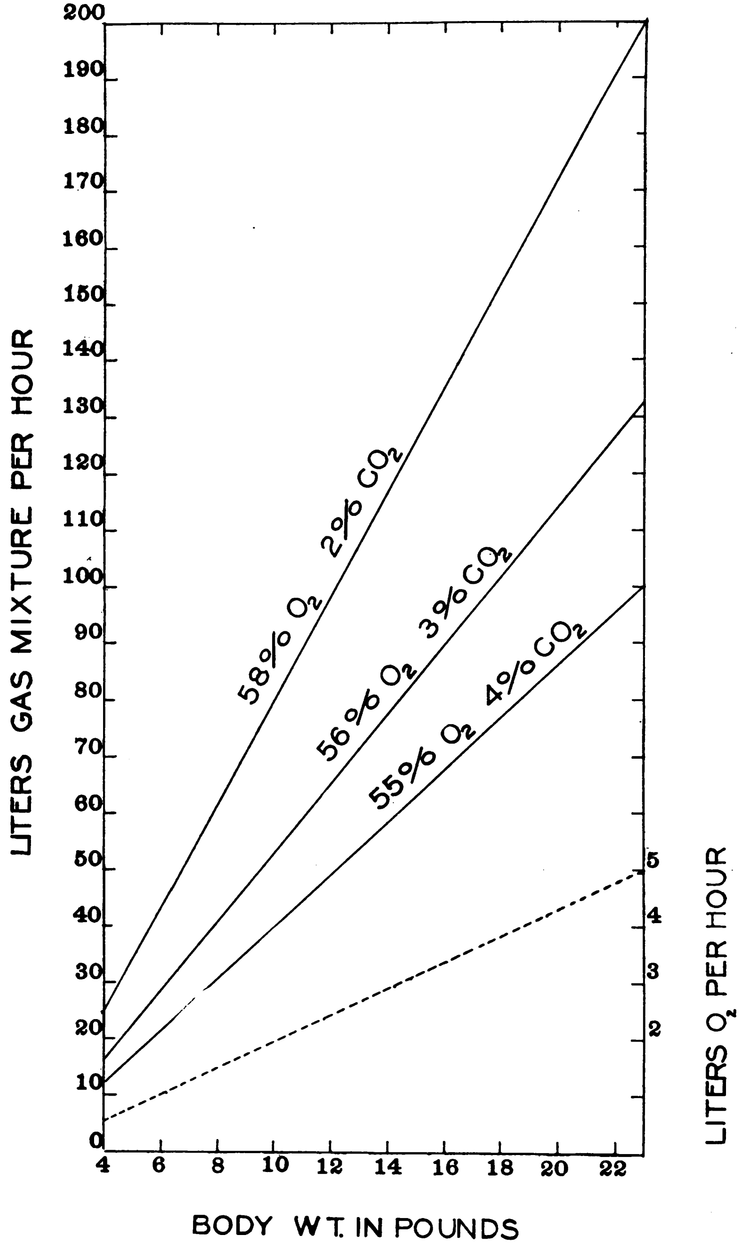

FIG. 5. THE RATE OF GAS FLOW FOR CARBON DIOXIDE AND OXYGEN THERAPY

Ordinate at left, rate of flow of gas mixture composed of equal parts of air and oxygen; ordinate at right, rate of oxygen intake per hour.

to permit the escape of the gas mixture flowing into the hood and which at the same time is of such a size as to prevent the influx of room air during inspiration from entering the hood and thus diluting the gas mixture. The oxygen is supplied from a compression cylinder and the air from a similar source or from a compressed air line. The concentration of oxygen in the hood is regulated by varying the relative rates at which oxygen and air are admitted.

It has been shown that 60 per cent of oxygen in the respired air can be used without injury to the lungs, but that higher concentrations may be dangerous. If, on the other hand, we attempt to safeguard the patient by reducing the oxygen concentration to about 40 per cent, much of the advantage of oxygen therapy will be lost. When air and oxygen are mixed in equal parts the resultant mixture contains 60.5 per cent of oxygen. If the gas mixture is allowed to flow at a sufficiently high rate, the oxygen consumed by the patient will have only a negligible effect upon the concentration of oxygen in the hood. This point will be made clear by reference to figure 5, in which the rates of flow are given for children according to their weight. Suppose, for example, that we desire to administer oxygen therapy to a child weighing ten pounds. This is accomplished by running the 60 per cent oxygen mixture through the hood at a rate of 80 liters per hour. To obtain this mixture it is only necessary to regulate the air flow at 40 liters per hour and the oxygen at the same rate as read off on the flow meters. Eighty liters of a 60.5 per cent oxygen mixture contain 48.4 liters of oxygen. Reference to the broken curve of figure 5 shows that a child weighing ten pounds will use up about 2 liters of oxygen per hour. The resultant mixture in the hood will consequently be about $\left[\frac{48.4 - 2.0}{80}\right]$ 58 per cent of oxygen instead of 60 per cent. Samples of gas withdrawn from the hood show that the oxygen does not depart from the calculated concentration by more than 1 per cent.

If it is desired to remove the carbon dioxide completely, then a blower similar to that used with a Benedict metabolism apparatus may be attached to the hood and the air kept in circulation through soda lime. On the other hand, if it is desired to administer carbon dioxide, then, by regulating the rate of gas flow through the hood, the carbon dioxide in the expired air may be built up to any desired level. When the gas flow through the hood is 50, 33 and 25 times as rapid as the rate of carbon dioxide excretion, then the concentration of carbon dioxide will be 2 $\pm$ 0.5 per cent, 3 $\pm$ 0.7 per cent, and 4 $\pm$ 1 per cent, respectively, the variations in per cent representing the individual variations in the metabolic rate of children of the same weight. As an example we may take once more the child of ten pounds. Such a child will excrete about (0.8 $\times$ 2) 1.6 liters of carbon dioxide per hour, which added to 80 liters will give a concentration of $\left[\frac{1.6}{80}\right]$ 2 per cent carbon dioxide. If it is desired to administer 4 per cent carbon dioxide to this child, then the gas flow must be reduced to 40 liters per hour. At this rate the oxygen consumed will reduce the oxygen concentration of the respired air to 55.5 per cent. This, however, is not a significant reduction.

It must be understood that by a few simple calculations any concentration of oxygen which may be desired can be passed through the hood by altering the relative rates of flow of oxygen and of air.

The hood may be used during the artificial respiration of the patient; or, with the lid left open, the respirator may be made quite as comfortable as a bed, while carbon dioxide or oxygen is administered to children who are breathing spontaneously.

ARTIFICIAL RESPIRATION OF CURARIZED CATS

In order to test the efficacy of our apparatus in cases of suspended or impaired respiration, a series of experiments was carried out upon cats whose respiration had been paralyzed by an injection of curare. An intraperitoneal injection of barbital-sodium rendered the cats quiescent and insensible to the operation involved by the insertion of a tracheal cannula. After the cat had been placed in the respirator, the tracheal cannula was connected to Tissot values and the minute volume of the normal breathing was determined by a collection of the expired air in a spirometer. The respiration was then completely suspended by an injection of curare through the external jugular, and respiration sustained by the respirator.

By means of the system of valves and vents attached to the air ducts of the pump and alternator, the pump can be made to create any degree or combination of pressures in the respirator which may be desired: positive alternating with negative, positive alone or negative alone, and any degree of pressure up to 50 cm. or more of water. The effect of these variations in kind and degree of pressure

TABLE 1

*Per cent deviation from the normal respiratory volume resulting from alternate positive and negative pressure, negative pressure alone, and positive pressure alone**

	Experiment	Deviation from normal respiratory volume at varying pressures (cm. H_2O)						
		4	6	10	12	15	20	30
		per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Positive and negative	1	−17	+27	+155				
	2				+44	+62	+280	+650
	3	−31	+84	+190		+303	+451	+766
	4		+1	+57		+193	+268	+563
	5		+27	+87		+192	+366	
	Average†	−24	+34	+122		+229	+362	+665
Negative only	1			+77		+165	+300	
	2				+65	+67	+339	+672
	3		−18	+170		+269	+427	+741
	4		−52	+1		+127	+211	+545
	5							
	Average†		−35	+83		+187	+313	+643
Positive only	1					−12	+10	+31
	2							
	3			−12		−6	−7	−7
	4			−40			−27	−12
	5			+3			+10	+18
	Average†			−16		−9	−3	+8

* The + sign signifies that the ventilation is in excess of normal; and the − sign, less than normal.

† Experiment 2 not included in average.

was measured by the volume of expired air collected in the spirometer per minute. The alternator was set to give 25 breaths per minute. The results of five experiments are given in table 1, which gives the per cent deviation from the normal respiratory volume. The same data are shown in graphic form in figure 6. The points give the average value for all experiments except no. 2, the omission of which will

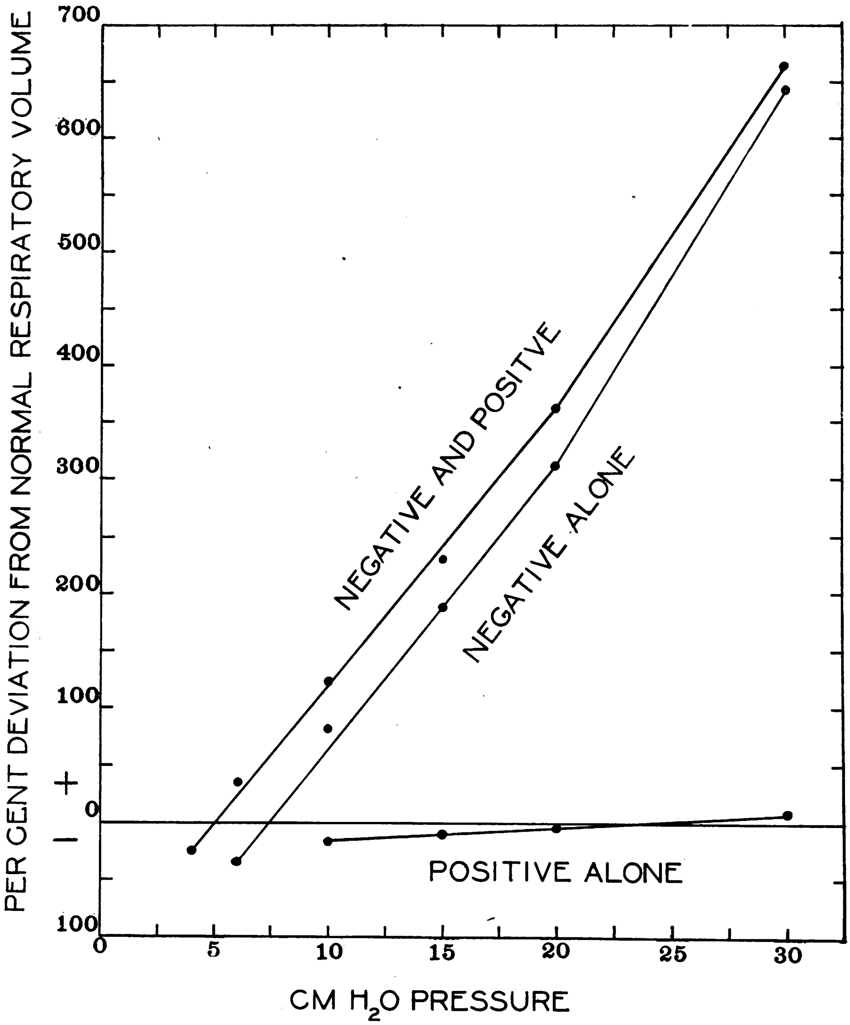

FIG. 6. RESPIRATORY RESPONSE OF CURARIZED CATS TO DIFFERENT PRESSURES

be explained. The points which fall below the 0 abscissa indicate the degree to which the ventilation was inadequate, those above the 0 abscissa indicating ventilation in excess of normal. It will be observed, from inspection of table 1, that there is a large individual variation in the respiratory response to a given pressure. At an alternating positive and negative pressure of only 6 cm. of water, the ventilation proved to be adequate in all cases except cat no. 2, in which case it was necessary to increase the pressure to 12 cm. in order to equal the normal respiratory volume.

As might be expected, the alternate application of negative and positive pressure was somewhat more effective than the negative pressure alone. The fact that an even greater difference does not occur is probably due to the fact that, when well stretched into the inspiratory position the chest tends to snap back to an expiratory position rather than to the normal resting position, thus expelling a certain amount of supplementary air. The curves under discussion indicate that even when an increase of 650 per cent of the tidal volume has been reached, there is no tendency for the thoracic wall to offer increased resistance to the stretching effect of the negative pressure; on the contrary, instead of becoming flattened the curves become slightly steeper. Since no pressures above 30 cm. of water were used we cannot say at what point the curves would commence to flatten out.

The positive pressure used alone was just sufficient to sustain the normal ventilation in four out of the five experiments, and showed but little tendency to increase with increasing pressure. This is about what we should expect in consideration of the fact that it is quite impossible to over-ventilate a human subject by the Schäfer method, which operates by positive pressure alone. Cat No. 2 proved to be so resistant to positive pressure alone that it was impossible to sustain life without the assistance of about 12 cm. of negative pressure, and was equally resistant to negative pressure until 20 cm. had been reached, at which pressure it approximated the average response of the other four cats. Except in the instance cited the ventilation was normal at an alternating positive and negative pressure of about 6 cm. of water. These results agree very closely with those of Philip Drinker and Shaw (1) using intact human subjects. They found that a pressure of 6 to 10 cm. of water was sufficient to cause normal respiration, while increased pressures caused a proportionate increase in the respiratory volume which was quite beyond the power of the subject to resist.

At intervals throughout these experiments the pump was shut off and the onset of cyanosis was followed by observing the color of the tongue, which was drawn from the mouth and held in a convenient position. After asphyxia had progressed as far as we deemed consistent with life, respiration was resumed and the normal color of the tongue returned in about twenty seconds.

An experiment was done to determine the effect of rate of respiration upon the volume of air taken into the lungs at a given pressure. It will be observed from inspection of table 2 that the tidal volume when

TABLE 2

Effect of respiratory rate upon the tidal volume, using alternate positive and negative pressures 22 and 37 times per minute

Pressure	Tidal volume	
	Rate 22	Rate 37
cm. H_2O	*cc.*	*cc.*
±6	23.1	23.8
±10	34.1	34.2
±15	54.1	52.8
±20	85.0	87.7

the rate of breathing is 22 per minute is practically identical to that obtained at a rate of 37. It becomes clear from these figures that the filling of the lungs is complete for any given pressure at all rates of breathing within the physiological limits.

SUMMARY

1. An apparatus has been described which will induce breathing in children suffering from respiratory failure. While the body is inclosed in an air-tight chamber, the head protruding through a rubber dam at one end, the chest and abdomen will rise and fall in response to alternating negative and positive pressures created within the chamber by means of an air pump.

2. By means of an air-tight chamber which fits over the head the carbon dioxide and oxygen content of the respired air may be regulated to meet the demands of carbon dioxide or oxygen therapy.

3. The operation and efficacy of the respirator has been tested upon curarized cats.

We wish to express our thanks to Mr. Frederick J. Christensen, Superintendent of the Machine Shop of the Harvard Medical School, for his co-operation and valuable suggestions in perfecting the technical details of our apparatus.

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