AN ELECTRONIC TIME CYCLED RESPIRATOR

BY

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The rhythmic inflation of the lungs, whether manually or by machine, is a well established procedure in anaesthesia and in the treatment of respiratory insufficiency. There is, however, a divergence of opinion as to the most suitable type of automatic respirator, and as to whether they are as efficient as or more efficient than manually controlled respiration. It must be remembered that the principles which have been established regarding cardiorespiratory effects apply equally to manual as to automatic respiration.

Much reliance is placed on the so-called "experienced" hand in manually controlled respiration. How many anaesthetists can estimate the amount of positive pressure used on inspiration, the amount of ventilation to 100 ml of gas per breath, or the length of the inspiratory and expiratory period, without the use of instruments? Maloney (1954) states that of 50 anaesthetists observed, 47 were unable adequately to estimate ventilation by manual and visual observance of the reservoir bag movement.

All types of intermittent positive pressure respiration, whether by hand or machine, impose a strain on the circulation by decreasing the pressure gradient which allows blood to flow from the great veins into the right heart. The positive pressure exerted on the lung alveoli tends to interfere with alveolar capillary flow; the higher the pressure and the longer the period over which it is exerted the more the capillary flow is occluded (Cournand et al., 1948; Motley et al., 1948).

This impairment of the circulation may be made minimal by manipulating the timing of the respiratory cycle and the pressure exerted, always subject to an adequate ventilatory volume. Providing ventilation is satisfactory the shorter the length of inspiration and the longer the length of expiration the more the heart is able to compensate for the circulatory depression due to pressure breathing.

It is evident that if pressure breathing is to be used three essential factors must be continuously and exactly measured and controlled; anything else is inspired guesswork. These factors are:

1. The pressure changes in the lung during the cycle.
2. The measurement of the expiratory volume.
3. The actual time taken by inspiration and expiration.

We have been concerned with time cycled (pressure limited) respirators for four years in preference to the more popular and more available pressure and volume cycled (pressure limited) machines.

The advantage of time cycling appears to be that the timing of the cycle can be set exactly to provide for minimum depression to circulation. Reference to figure 1 shows a pressure volume diagram constructed for a patient. It will be seen that with inspiration at 1.25 sec and a pressure of 10 cm H₂O, the same ventilation can be produced as with a pressure of 8 cm H₂O and an inspiratory period of 2 sec. In the first instance the total pressure period in the minute is 18.75 sec whereas in the second instance the pressure period is 30 sec, the shorter inspiratory period allowing the heart an extra 11 seconds in the minute in which to work unimpaired. Spalding (1955) demonstrated that, providing there is no obstruction to respiration, the amount of tidal air is almost proportional to the inspiratory pressure, and that a large proportion of the tidal air enters during the early part of inspiration. He showed, and our figures agree with his, that adequate tidal air (subject to a satisfactory instantaneous airflow) may be obtained by an inspiratory period of 0.6 sec and that little is to be gained by prolonging it beyond...
1.5 sec. We have rarely used a period longer than 1.25 sec, the respiratory rate varying from 12 to 18 per minute. It is simple to compose a pressure volume diagram for each patient at different inspiratory lengths which may help in the choice of the best combination of pressure and time for the required expiratory volume. The respiratory volume was determined from the Radford (1955) nomogram corrected for anaesthetic factors. This volume was taken as a guide to the minimum volume of respiration necessary for adequate ventilation. When in doubt we have collected end expiratory gas from the trachea by means of fine polythene tubing and analyzed the gas for CO₂ percentage by means of a Draeger analyzer. This method, while not very accurate, is clinically useful.

Time cycling does not suffer from the disadvantage of pressure cycling machines where a leak in the gas circuit may lengthen the inspiratory period until such time as the leak is big enough, when the whole cycling mechanism fails, as the cycling pressure is never reached. Gordon et al. (1956) have demonstrated an advantage of the time cycled machine over the volume cycled machine, in that the shape of the inspiratory curve, curve I (time cycled), is more physiologically ideal than curve II (volume cycled) and produces less cardiac impairment.

We have constructed these machines on a one-way circuit so that it is possible to meter exact percentages of gases to the patient, which is of advantage when using nitrous oxide. The cost of this increased gas flow is repaid by savings in use of soda lime and the lessened use of analgesics. The further advantage of an open circuit is that there is no question of increased carbon dioxide due to channelling or altered absorption by the soda lime. Gaensler (1956) in an experiment demonstrated that a conscious volunteer breathing in a closed circuit system with a conventional 1 lb. canister of soda lime increased his ventilation from 6 l./min to 20 l./min in the first 45 minutes. He concludes that the ordinary 1 lb canister is reasonably efficient for 15 mins of respiration. The addition of an electronic triggering device subject to any dominant rhythm between 12–60 respirations per minute increases the scope of the machine, as it may be used when spontaneous respiration is allowed or on the conscious patient with respiratory insufficiency where it has shown itself to be comfortable.

Variants of the machine have been used by one of us in over 600 thoracic operations (table 1) and more than 100 nonthoracic cases as well as a few cases of respiratory incapacity arising from disease or drug overdosage. The longest period of continuous use has been 60 hours. The ages of the patients have varied from 10 to 72 years. In no case was a negative phase used because of any deleterious effects on the cardiovascular system even though massive haemorrhage has occasionally occurred. A negative phase of
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**Table I**

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pneumonectomy</td>
<td>100</td>
</tr>
<tr>
<td>Thoracotomy</td>
<td>75</td>
</tr>
<tr>
<td>Lobectomy (and lingula)</td>
<td>158</td>
</tr>
<tr>
<td>Segmentals and wedges</td>
<td>117</td>
</tr>
<tr>
<td>Diaphragmatic hernia</td>
<td>4</td>
</tr>
<tr>
<td>Mitral valvotomy</td>
<td>62</td>
</tr>
<tr>
<td>Patent ductus</td>
<td>4</td>
</tr>
<tr>
<td>Oesophagectomy</td>
<td>6</td>
</tr>
<tr>
<td>Pericardial cyst</td>
<td>1</td>
</tr>
<tr>
<td>Hydatid cyst</td>
<td>1</td>
</tr>
<tr>
<td>Retrosternal thyroid</td>
<td>3</td>
</tr>
<tr>
<td>Repair oesophageal fistula</td>
<td>2</td>
</tr>
<tr>
<td>Repair bronchial stump</td>
<td>4</td>
</tr>
<tr>
<td>Cysts of lung</td>
<td>4</td>
</tr>
<tr>
<td>Decortications and 1st stage thoracoplasty</td>
<td>59+</td>
</tr>
<tr>
<td></td>
<td>600+</td>
</tr>
</tbody>
</table>

-5 to -10 cm H₂O has, however, been found extremely useful in the type of case in which expiration is prolonged and the lungs rigid.

The negative pressure has been obtained by adding a T-piece to the expiratory outlet attached to a sucker, the negative pressure being controlled by a variable orifice. The expired air has been measured by a Cowan and Parkinson dry gas meter graduated to read 1500 ml on one revolution and in the latest machine by a Wright's anemometer (to be fitted).

**THE RESPIRATOR**

The machine consists of a gas circuit with electromagnetically operated gas valves controlled by an electronic circuit.

(a) **Gas Circuit** (fig. 2).

Anaesthetic or other gases flow continuously under a pressure of approximately 5 lb./sq.in from a Boyle's or similar machine into a 1.5 litre rubber concertina bag; a spill valve is fitted to prevent overdistension. A large coil spring whose tension is adjusted by a manually operated worm drive gear applies pressure to the bag and thus controls the pressure within the gas circuit.

Two alternative methods have been used with success; a sliding weight on a bar attached to the top of the bag and at the other end to a fixed pivot allows equally close control of pressure, this depending on the position on the bar at which the weight is clamped. A Walton 4 Mixing Valve eliminates the need for a rubber bag altogether and permits instantaneous flow rates of up to 180 l./min but requires an input pressure of 10 lb./sq.in and cannot, therefore, be attached to a Boyle's machine without special adaptation. The pressure in the gas circuit can be varied between 5 and 30 cm of water pressure. The flow from the bag is controlled by a gas valve of piston or poppet type the stem of which is operated by the extended armature of a solenoid. From this gas valve the gases pass through wide, smooth bore, nondistensible plastic tubing to a Y junction at the anaesthetic mask or intratracheal tube adaptor, at which point a manometer is connected. Exhaled gases flow through a parallel length of plastic tubing to a second solenoid operated gas valve which opens to atmosphere but to which a negative phase device or an anemometer can be attached. Instantaneous or peak flow of the apparatus is of the order of 80 l./min which, although not attaining the ideal of 100 l./min, is efficient (Proctor, 1955).

(b) **Electronic control device** (fig. 3).

The control device is a free running transistor multivibrator. In this circuit two transistors conduct alternately, switching each other automatically, the length of time of conduction of each depending upon the value of coupling capacitors and their leak resistors. The latter are variable and can be adjusted to allow periods of conduction varying from 0.5 to 4.5 seconds. The multivibrator circuit opens and closes a relay through an output transistor and the contacts of this control the gas valves. One gas valve is thus indirectly connected to one of the two transistors of the multivibrator, the other gas valve to the remaining transistor of the pair. As each transistor conducts, its associated gas valve opens for a period governed by the setting of the leak resistance thus permitting independent control of both inspiratory and expiratory periods. The control, being by variable resistances, is infinitely variable and not by steps. The gas valves can never be both open or both closed; switching is instantaneous, positive and with a short transition period.

(c) **Trigger device.**

The gas valves have one-way valves incorporated in them and a tambour is connected into the gas circuit between the two main valves. In
A. Gas inlet.
B₁, B₂, B₃. Automatic/Manual control (shown in "automatic" position in main diagram: inset shows "manual" position).
C. "Concertina" bag.
D. Lever and spring.
E. Shut-off valve, preventing over distension of bag.
F. Excess pressure release valve.
G. Solenoid operated valve controlling inspiratory phase.
H. Nonreturn valve.
I. Connection to face mask or endotracheal tube.
J. Nonreturn valve.
K. Tambour.
L. Microswitch.
M. Solenoid operated valve controlling expiratory phase.
N. Connection to manual bag.
O. Outlet to atmosphere or spirometer.
P. Flexible tubing to patient.
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the event of the patient attempting to inspire during the expiratory phase, a negative pressure is produced as the one-way circuit valve discloses, and the movement of the tambour diaphragm operates a microswitch which short circuits the variable leak resistor controlling the inspiratory valve. The multivibrator immediately switches and opens the inspiratory valve and gas under controlled pressure inflates the lungs. The rise in gas pressure immediately opens the microswitch and the multivibrator reverts to its former rhythm. By setting the multivibrator to the longest expiratory period the patient can trigger the machine continuously and weak inspiratory efforts can be assisted.

(d) Manual operation.

By a single movement of a lever the machine can be switched out of the anaesthetic circuit and manual control of respiration instituted. The lever diverts the incoming gases from the concertina bag into the manual control bag held by the anaesthetist and makes direct connection between this and that part of the gas circuit between the two gas valves.

(e) Use with explosive anaesthetics.

Thermionic valves can be used in the electronic circuit in place of transistors, but their use not only increases the bulk but, because of the heat dissipation, prevents use of explosive anaesthetics and renders the construction of hermetically sealed units very difficult. Transistors operate at very low power and their heat dissipation is negligible. The transistor control unit is here sealed hermetically in a metal box, ceramic sealed terminals being used for electrical connections and oil filled variable resistors with sealed spindles being the only controls other than the trigger switch brought to the outside of the case. The trigger switch operates on a current of 9 mA at 10 volts d.c. in a noninductive circuit. This, the only unsealed unit, is to be considered as an essentially safe circuit as defined in the
Time/bronchial pressure tracings using a capacitance manometer and a recording oscilloscope. All from same patient. Tidal volumes between 350-480 ml. Peak pressures between 11-16 cm H₂O. Chest open.

Ordinate = pressure; Abscissa = time (1/10 sec intervals).
A. Barnet respirator (time cycled)
B. Pask respirator (pressure cycled)
C. Beaver respirator with solenoid valves (volume cycled)
D. The Stephenson minute-master (pressure cycled)
E. Pneumotron (time cycled)
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MINISTRY OF HEALTH REPORT—Anaesthetic Explosions 1956, Section V, para. 18.

The solenoids and their voltage rectifiers are individually hermetically sealed and the machine when efficiently earthed can safely be used with explosive anaesthetics.

The various units are mounted in an enclosed metal case with the controls upon the front panel. A pointer connected to the moving top plate of the concertina bag is visible through a slot in the panel and its position and range of movement is thus rendered visible. A compartment in the back of the case contains the electrical supply cable and the plastic tubing and connections during transportation (figs. 5, 5A, 5B).

(f) Power supply.

The machine can be operated from the mains or from an accumulator requiring 33 watts for piston valves and 6 watts for poppet valves. The use of the latter permits a dry battery to be used for limited periods.

SUMMARY

A time cycled intermittent positive pressure respirator has been described having the following characteristics:

(a) Readily portable and operable from either mains or accumulator.

(b) Being inserted between an anaesthetic machine or other gas supply and the patient, it will operate from the normal rate and pressure of gas flow used for manual control of respiration by intermittent positive pressure (i.e. approximately 8 l./min at 5 lb./sq.in pressure).

(c) Will permit infinitely variable adjustment of the inspiratory/expiratory ratios between 9:1 and 1:9, respiratory rates between 12 and 60 respirations per minute at an inspiratory period 0.5 sec and peak bronchial pressures between 5 cm and 30 cm of water pressure.

(d) Will produce bronchial pressure curves corresponding to the natural tidal volume curve and independent control of the length of inspiratory and expiratory periods.

FIG. 5
Exterior view of respirator.
FIG. 5A

FIG. 5B
Interior views of respirator.
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(e) A high instantaneous flow rate (80 l./min), permitting a short inspiratory period with adequate ventilation.

(f) Operates as a one-way gas circuit without rebreathing.

(g) Allows the patient to trigger the machine which then reverts to its own rhythm until triggered again, the filling of the reservoir bag being adjusted to at least twice the tidal volume of the patient.

(h) Gives visual warning of respiratory obstruction, the bag slowly or rapidly filling to its maximum capacity with diminished tidal excursions.

(i) Permits rapid transfer to manual control of respiration without disconnecting the respirator from the source of gas or the patient.

(j) The electronic and electrical circuits being either hermetically sealed or essentially safe circuits, permit the use of explosive anaesthetics or the operation of the machine in a potentially explosive atmosphere.

ACKNOWLEDGMENTS

We wish to thank the Barnet Group Hospital Management Committee for a grant; Messrs. W. Watson and Son Limited for constructing a set of valves; Messrs. British Oxygen Co., Dr. D. M. H. Cogman and Messrs. Pye Radio Ltd. for providing the photographs; and the surgeons of the Barnet Group of Hospitals for their co-operation.

REFERENCES


BOOK REVIEW


The great reduction in surgical mortality which has taken place since the war has been mainly due to an increasing knowledge of the correct preparation and aftercare of the patient rather than to an improvement in technical skill. The steady spate of articles and monographs has made it difficult for surgeons and anaesthetists to keep up to date with this knowledge and at the same time not to be confused by many of the differing opinions. There is, therefore, a need for a book which can present a balanced picture of modern pre-operative and postoperative care. The subject of this review, the text of which is published in German, attempts to do this.

The authors have managed to cover the whole subject within 250 pages and yet very few subjects are inadequately dealt with. The disturbances of water and electrolyte metabolism and their correction form the major part of the book and are lucidly explained, although in the section on burns Wallace's "Rule of Nine" is made unnecessarily complicated. The care of neurosurgical and thoracic patients is well discussed and the illustrations in these sections are excellent. The section on infections is not very clear and no mention is made of any antibiotic more recent than the tetracyclines. In a book of this length, it would seem inappropriate to spend five pages on tetanus—surely a reflection on Continental asepsis.

On the whole, this book is an excellent comprehensive review of its subject. In addition to the language barrier, it has one major defect in that most of the drugs mentioned are given proprietary names and their true nature and British and American counterparts can only be guessed at.

Anthony R. Anscombe