THE DESIGN AND APPLICATION OF POSITIVE PRESSURE RESPIRATORS

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If a condition arises in which tracheotomy is desirable and artificial respiration is required, I believe positive pressure to be the method of choice because:

- (1) Access to the patient for every purpose is facilitated.
- (2) The problem of avoiding the tracheotomy with the neck-seal is avoided.
- (3) Humidification is easy.
- (4) The patient is physically and psychologically less constrained.
- (5) The necessary apparatus is less bulky, cheaper and easier to store.
- (6) It provides extremely efficient respiration and is obligatory in many conditions, e.g. 'flail chest'.

The method is not new, in fact mouth-to-mouth insufflation of the new-born is centuries old, while the anaesthetist has 'squeezed the bag' for at least 25 years. This method was employed by Professor Lassen in the great Copenhagen epidemic of 1952; using relays of students he saved a significant proportion of cases of bulbar poliomyelitis, whereas his 'iron lungs' proved fruitless.

This is not to deny the value of cabinet respirators (with tracheotomies) for they are particularly used in the U.S.A., but it is a difficult technique.

In 1952-53 the Ministry became concerned about the possibility of a similar epidemic in London, on a vaster scale. They seemed dubious about a supply of devoted students to squeeze bags. As it happened, I was making a small machine for just this purpose. Dr. Godber asked me to convert this machine for use in respiratory paralysis, using the resources of the National Hospital, Queen Square. After a frantic and frustrating time we succeeded and, having eventually interested the British Oxygen Company, 186 machines were built in nine weeks.

Frustration was due to the difficulty of finding geared motors and the complete lack of interest of industrial concerns in supplying small quantities of anything. Fortunately much anaesthetic equipment could be converted and by devious

means I discovered the Parvalux motor (disguised under other people's names) which was successful and is in fact still used in the Radcliffe and in some of my machines.

It is necessary that any apparatus should have the confidence and understanding of those who use it. Complete reliability is essential and simplicity in construction and use almost equally desirable. If possible, uniform apparatus should be used throughout a department.

The apparatus consists of five essential parts:

- (1) A machine to deliver air.
- (2) A humidifier to warm and moisten it.
- (3) A valve or valves to permit inspiration and expiration.
- (4) A suction connection to—
- (5) The tracheotomy tube.

Generalizing, machines are of two types (1) 'Volume-cycled', where a fixed charge delivered at each stroke; and (2) 'pressure-cycled', where the patient is filled to a predetermined pressure which initiates the expiratory phase. (So-called 'time-cycled' machines in fact can be classed under one of the two previous definitions.)

'Volume-cycled' machines are mainly electrically-driven pumps utilizing room air. 'Pressure-cycled' employ air previously compressed either in cylinders or by separate generator.

The most popular machines in Britain have proved to be 'volume-cycled'. This is probably because:

1. The machines are easier to make and understand and their faults are at once obvious. Accordingly, they could be turned out rapidly in the early, rather amateur, days.
2. Controls are simple and separate, whereas in the other type they are generally over-sensitive and tend to interact.
3. 'Pressure-cycled' machines have the serious danger that, with any blockage, the pressure will rise rapidly and cycling will occur. Should there be a significant leak the inspiratory phase can be indefinitely prolonged.
4. Cylinders of compressed air are bulky and the number used is alarming. In some cases, air entrainment via a venturi enables economies to be made.

FIG. 1.—A typical Beaver volume-cycled respirator.

Most 'pressure-cycled' machines are highly ingenious and have to be beautifully made. But they do have the above disadvantages and I must leave them at that.

Whatever the machine, certain values obtain:

1. *Speeds* should be variable in about a 2 : 1 ratio from 16-32 r.p.m. If set speeds were requested I would wish: 17 for adults, 22 for special cases with small alveolar space, and 27 for children.

Beyond these speeds serious problems of air flow may arise. It must be realized that the peak flow rate is about 40 litres per minute. With a cross-section of 1 sq. cm. this corresponds to a flow rate of some 7 metres per second, or 15 m.p.h. I am not considering neonates as I believe they need very special equipment.

2. *Pressure*. About 12 cm. of water is normally needed to maintain adequate inflation of all parts of the lung. To avoid the danger of emphysema 22 cm. will not usually be exceeded and 12-24 cm. is therefore the normal range.

3. *Phasing*. Inspiratory-expiratory phasing is in the ratio of about 1 : 2. It should not be less, and the rise of flow rate—i.e. the 'pressure curve'—should be rapid but not excessively so. This may lead to over-distension of proximal alveoli with 'air trapping' and starvation of the periphery.

It must be remembered that a 1 : 2 ratio mechanically may well be far less than this atmospherically owing to various delaying factors in the delivery of air.

4. *Volume*. This always needs to be larger than anticipated or calculated from Radford's nomogram. The reasons for this are (1) the extremely unphysiological method of breathing, resulting, I believe, in an increase in the physiological dead space, and (2) perhaps lessened alveolar capillary blood flow. The effect, too, of secretions must not be ignored. In round figures somewhere between 4 and 9 litres per minute are usually required.

Spirometry is performed on the outlet side for obvious reasons, and generally a conversion of the domestic gas meter by Parkinson and Cowan or Wilson is used. Alternatively, inferential meters such as the Wright, Barnett or Draeger are used. From volume and pressure readings and the comfort of the patient a degree of ventilation is chosen. This will almost always be found to be on the side of hyperventilation and I believe the normal proprioceptive system controlling respiration is largely inactivated. The measure of content would seem to be the adequate distention of the whole lungs—'a good chestful of air'. A PCO_2 below 20 mm. is quite common and has never been found to cause any harm.

In the early stages of respiratory failure we normally add some 3 litres of oxygen per minute, producing more or less 50% oxygen and nitrogen. This adds considerably to the patient's comfort and produces oxygen hypersaturation. A falling volume with increased pressure means some extra resistance from blockage or increased lung compliance. Falling pressure *and* volume means a

leak. Increasing volume with or without pressure fall means diminished compliance or the removal of a previous block.

5. *Negative phase.* Physiologically, to reduce the mean intra-thoracic pressure is very desirable, but in practice no benefit has been found to result. In anaesthesia, however, it is useful with the open chest to control lung expansion. Under no circumstances should the negative phase exceed 5 cm. of water or oedema of the lung may occur.

6. *Patient triggering.* When the patient has adequate muscular power to resist respiration it might be thought that a machine which would follow his breathing pattern would be very useful. Unfortunately they seldom do their duty adequately and recourse must be made to a constant-running pump, the patient being sedated and cajoled into following.

Such triggering is best suited to pressure-cycled, compressed air machines and the patient signal is derived from the small depression caused by his inspiratory effort. In all such machines:

- (a) The response should be to less than $\frac{1}{2}$ cm. of water depression.
- (b) Delivery of air should be almost immediate.
- (c) There should be an open passage so that the patient will not stifle if triggering failed.
- (d) An automatic cycle should cut in if no patient signal is received in about 8 seconds.

Considering these features it should be easy to construct an adequate and simple machine using electric power. There are, however, difficulties.

The *pump chamber* itself is inevitably made of rubber bellows which are fallible and I believe it would not be impossible to use a metal cylinder with P.T.F.E. piston, lubricated by water.

Volume is easily controlled by variable leverages.

Speed is difficult. With a variable load an electric motor is extremely difficult to control unless brush motors are accepted. These, I believe, to be undesirable, though very beautiful control is possible by electronic means, using thyratrons or transistors; less beautiful using a governor as in the Kenwood domestic mixer. Without brushes some mechanical gearing must be used. Almost every form of variable belt, gearbox, and friction of hydraulic drives has been used. Fortunately 2 : 1 variation mentioned before is within the compass of most.

Size. I believe the advantages are all with the relatively small machine and the temporary fashion for vast monsters has waned.

The small machine is so much cheaper and easier to store. It can be used as a 'portable' by means of a rotary converter or by an inbuilt

12-volt motor. The reliability factor is not necessarily any less.

Gas from the machine is delivered through tubing which should not be too rigid. If the normal corrugated tubing is used it will absorb and waste a considerable volume by expansion. But too rigid tubing will transmit unpleasant shock waves and vibrations to the patients.

Humidification is essential to keep the bronchial secretions sufficiently moist for aspiration. By far the simplest and best is the thermostatically-controlled water bath, described by Drs. Spalding and Marshall. Temperatures between 100° and 150° F. are generally employed and sufficient moisture obtained. There is no need to supply more which results in continuous sucking of excess moisture.

Valves to enable expiration after the pressure stroke. There are two main types: (1) Atmospheric valves which are operated by the air flow. They are simple, can be fitted near to the patient and in the ultimate end always work. But they are tricky and prone to become water-logged. (2) Mechanical valves can be worked off the machinery via wires, solenoids or by hydraulic means if in the distant position, or off a camshaft if on the machine. In the latter position there is need for two-way tubing and the whole set-up liable to be flooded with water. Again, for manual operation the flap valves must be used.

I believe these positive valves are desirable, giving definite timing and greater reliability in general. They are essential with most types of negative phase as a 'flap' valve is held shut by the suction. The pressure gauge connection is always made beyond the valve and as near to the patient as possible.

Suction connections. We tried all the usual connections and finally produced one of our own.

Ribbed aluminium nipples are screwed into two arms of a T-shaped tube. The third arm has a screwed cap to enable the suction catheter to be passed down. The two nipples are changeable, there being various sizes. They are not screwed up tight and, being able to twist, provide a universal joint effect, enabling the patient to be turned and moved without twisting the tube in the trachea. The whole connector is very small and light and has proved a great success.

Tracheotomy tubes. Almost every one of these was in existence well over a century ago. Which to use depends on choice and local politics. But in any case, for this purpose, it must bear an inflatable cuff or be a very close fit.

Further requirements are these:

- (1) The wall thickness should be as thin as practicable, providing as large a lumen as

possible compared with the outside diameter. The importance of this will be realized by the fact that the resistance to air flow is proportional to the 4th power of the diameter.

- (2) The material must be atraumatic.
- (3) The tube should provide a smooth easy air path and enable the suction catheter to be passed easily.
- (4) It must have some positive means of end-wise location (e.g. fixed flange), otherwise it can all too easily abut on the carina or enter the right main bronchus.
- (5) The tubes must be easily available and not be absurdly expensive.

We personally used old-fashioned, flanged Morant Baker tubes in rubber. On these we place inflatable latex cuffs which may be fluted in the larger sizes. I think we are very satisfied with them and can boast the outstanding record of only one case of tracheal stenosis in nine years, and this not attributable to the tube.

We do not deflate the cuff as a routine as

recommended in some quarters. I believe this to be wrong. As an anaesthetist I know that it is movement of a tube which causes laryngitis and tracheitis and not the presence of a cuff.

Suction is applied as required or about every 20 minutes. Jaques or Tiemann catheters in rubber are used and the catheter nipped, or suction released, when it is moved.

This brief resumé indicates the problems and some of the answers in this form of respiration. Above all, nursing and constant vigilance are essential and even some small mistake can be fatal. Warning devices give a false sense of security and there must be no dim lights at night. But by and large the method is a complete success. It will keep alive patients otherwise hopeless and, with many others, provides far easier and more comfortable treatment than a 'lung'.

A certain most important person at the Queen Square Centenary asked me the question I still can't answer: 'Why was this not done before, instead of the complication of cabinet respirators?'