AN APPARATUS FOR ARTIFICIAL RESPIRATION ("IRON LUNG")

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In the case of a disturbance in the functioning of the respiratory muscles, for instance in cases of suspended animation or paralysis, artificial respiration must be applied. This is made possible even when the condition is of long duration by an apparatus which causes a periodic expansion of the lungs ("iron lung"). On the principle of Drinker the patient's body is enclosed in an air-tight chamber in which alternations of pressure are generated, while the patient's head remains outside the air-tight chamber. In the apparatus on this principle developed by Philips the chamber is made so large that there is space for the doctor or nurse in addition to the patient, for the purpose of carrying out the operations necessary for the treatment. The way in which the alternations of pressure are brought about in the fairly large chamber (volume 1.5 m³) is described. The driving mechanism is balanced in such a way that upon any interruption of the current from the mains which supply the motor, the apparatus can easily be operated for many hours by hand.

The problem of resuscitation by artificial respiration in cases where the normal respiratory movements have ceased is an old one. Such cases of apparent death, where artificial respiration is indicated, occur especially in the case of victims of drowning or electrical shock or in cases of poisoning by carbon monoxide, etc. The methods of artificial respiration which are usually applied are based on attempts to cause an expansion of the thoracic cavity (inspiration) by movements with the arms of the patient, which by means of the upper arm muscles attached to the chest are able to exert a pulling force on the pectoral wall. Another method is to attempt by direct pressure on the chest to press the air out of the lungs and to allow them to suck in air by means of the elasticity of the pectoral wall. All these methods are fairly primitive, they require great exertion on the part of the person applying them, and they are practically only suitable for use during a few hours. In many of the above-mentioned cases the latter is no objection since the purpose is to remove a condition which is of short duration only. There are, however, also cases where the condition of disturbed natural respiration may last for weeks or months. The most familiar example is the paralysis of the respiratory muscles which may occur as a result of epidemic infantile paralysis. With such cases in view attempts were made to construct an automatically working apparatus which can assume the functions of the respiratory muscles for any length of time desired. With the help of such an apparatus it is in the above-mentioned cases of infantile paralysis not only possible to keep the patient alive, but often to effect a cure. It often happens that the initially occurring disorder is very extended, and that for instance the muscles of arm, leg and respiration are paralyzed, while in the course of weeks a recovery of function occurs due to cure of the inflammation process in the central nervous system which had caused the paralysis.

Mechanization of artificial respiration

Among the different methods for the mechanization of artificial respiration that of Drinker¹ has proved the most satisfactory. The body of the patient is introduced into an air-tight chamber, while his head remains outside. In this chamber a periodic alternation of pressure is caused. Since the lungs, by way of the mouth, remain in connection with air at normal pressure outside the air-tight space, a movement of inhalation takes place upon decrease of the pressure on the chest and abdominal wall, while upon recovery of the normal pressure or the exertion of extra pressure on the chest, an exhalation movement is carried out.

In principle, the air-tight chamber in which the body of the patient is enclosed, needs only to be large enough for the patient's body. In the first instance it would seem advisable not to make the chamber any larger than necessary since the required alternation of pressure is easier to bring about in a small chamber than in a large one. If, however, the body of the patient is enclosed in a narrow box (as was done in the first apparatus built on the Drinker principle), there are very undesired consequences in connection with the care of the patient. It is obvious that the treatment requires other things besides artificial respiration. For all kinds of daily occurrences such as care of the skin, massage and exercise of paralyzed limbs, the patient must be removed from the apparatus. When this is done artificial respiration ceases, and the patient begins to suffocate. Attempts have been made to

¹) In the choice of the method to be used, we were advised by Prof. Dr. A. K. M. NOYONS of Utrecht.
find a solution for this difficulty by allowing the patient to breathe in a certain amount of oxygen so that the lungs will have a reserve available. In spite of these precautions it is still found necessary to let the “iron lung” resume its function as quickly as possible. It is obvious that this circumstance is very unpleasant and even terrifying for the patient, and requires a high standard of skill of the personnel in charge. Serious doubt may even be felt whether in this way adequate care can be given, especially since it is a question of careful nursing in many cases of infantile paralysis which makes it possible to save the patient.

It was this consideration which led in the construction of the Philips apparatus for artificial respiration to the decision to deviate from the ordinary design. The chamber into which the patient’s body is introduced is made so large (see fig. 1) that the doctor or nurse can take his place in the chamber beside the patient. Artificial respiration is now only interrupted for a few seconds when some treatment or other is necessary, namely only long enough for the door of the chamber to be opened for the entry of the one giving the treatment.

**Driving power of the “iron lung”**

The most important problem in the construction of the “iron lung” was the excitation of the required alternations of pressure in the chamber. This is accomplished by periodically increasing and decreasing the volume of a container (air bellows) connected with the chamber. The principle of this process is shown in fig. 2, while fig. 3 is a photograph of the driving mechanism. In order to be able to adapt the magnitude of the pressure differences, as well as the rhythm in which they occur, to the age and condition of the patient.

![Fig. 1. The “iron lung” in action.](image-url)

![Fig. 2. Diagram showing the principle of the mechanism for generating the pressure alternations in the “iron lung”.](image-url)
patient, the length of the arm $a$ (and thus the stroke of the bellows) can be varied, and the shaft is driven via a pulley with five sheaves of different diameters which permits adjustment at different rates of breathing.

The required dimensions of the bellows are calculated in the following way. The difference $\Delta p$ between the highest pressure $p_1$ and the lowest pressure $p_2$ in the chamber must amount to 0.03 atmosphere in the most extreme case. When we assume that the pressure alternations take place isothermally in the chamber $^2$), the product of pressure times volume is constant. Therefore if $v_1$ is the volume of the chamber and $\Delta v$ the increase of volume due

\[ p_1 v_1 = (p_1 - \Delta p) (v_1 + \Delta v) \]

and by approximation

\[ \Delta v = \frac{v_1}{p_1} \Delta p \ldots \ldots \ldots (1) \]

In our case $v_1 = 1.5 \text{ m}^3$ and $p_1 = 1$ atmosphere approximately, so that one finds with $\Delta p_{\text{max}} = 0.03$ atmospheres

\[ \Delta v_{\text{max}} = 45 \text{ litres.} \]

Fig. 3. The mechanism of the “iron lung”. On the left the chrome leather bellows, whose expansion causes a decrease in pressure in the chamber. On the right hand the motor which moves the driving rod of the bellows via a pulley with five sheaves of different sizes, a worm drive and a lever. By means of the fivefold pulley the breathing rate can be adjusted.

This volume of air must be added and removed from the chamber at each respiration. The cross section area of the bellows is about 1600 cm²; the movable flange of the bellows must therefore be able to be moved a distance $s = \Delta v/y = 28$ cm back and forth.

Upon expansion of the bellows considerable work must be done in opposing the external atmospheric pressure; at the greatest expansion of the bellows, when the chamber is at a decreased pressure of 0.03 atmosphere, the atmosphere presses against the movable flange with a force of $1600 \times 0.03 \times 1.033 = 50$ kg. The energy supplied during the expansion of the bellows can, however, be recovered when the external atmospheric pressure is

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2) Actually, at the frequencies of respiration (15 to 30 per minute), a temperature equilibrium between the volumes inside and outside the chamber will not continually be established. With perfect heat insulation, the pressure variations would take place adiabatically, and $p \propto$ instead of $p v$ would be constant with $\propto = 1.4$. In practice a polytrope with $1 < \propto < 1.4$ will best approximate the truth. One then in any case obtains a certain change of pressure with a smaller volume change than in the case of an isothermal variation. The capacity of the bellows, which is calculated in the following, is therefore larger than is theoretically necessary. The reserve, which is available in this way is of practical advantage since the pressure variations are decreased by different leaks in the chamber which will be discussed.
allowed to do work during the contraction of the bellows, for instance by causing it to raise a weight which produces energy again as the bellows expand. In this way it is possible to use a low-powered electromotor (\(1/4\) h.p. in our case). It is, however, of greater importance that this method of balancing makes it possible to work the bellows by hand without appreciable exertion. This latter factor is essential, since upon any disturbance in the electric mains which feed the motor, artificial respiration must not stop, and the “iron lung” must be able to be kept in action for several hours by a nurse.

The method of balancing the external pressure will be examined in more detail. For the sake of comparison one may recall the way in which a lift is balanced; the lift is coupled with an equal counter weight which moves the same distance downward as the lift moves upward. In the ideal case the couples which act on the axis of the cable drum are in equilibrium at every moment, so that the motive force needs only to overcome the frictional and mass forces. In the “iron lung” mechanism also the aim will be to provide that at every position of the bellows the air pressure is kept in exact equilibrium; in this case, however, in contrast to the example of the lift, the force to be balanced is not constant during the motion of the bellows. With the help of equation (1) one finds for the force \(q \times \Delta p\) on the movable flange of the bellows

\[
q \cdot \Delta p = \frac{q \cdot P_1}{v_1} \Delta v = \frac{q^2 P_1}{v_1} \cdot x, \quad (2)
\]

where \(x\) represents the displacement of the flange. The mechanism shown in fig. 4 serves to balance this force. The driving rod \(D\) of the bellows is coupled with the shaft \(A\) via a sliding block \(B\) and a slotted bar \(K\). By a gear transmission in the ratio \(n : 1\) the shaft \(C\) is coupled with \(A\), and to \(C\) is fastened a lever \(H\) with the variable length \(h\) and a weight \(G\). At the initial position of the bellows when the same pressure holds inside and outside the chamber, the lever \(H\) stands vertical and the weight \(G\) is therefore at its highest position, while upon expansion of the bellows the weight \(G\) turns toward a lower position.

It is easy to calculate to what degree the ideal of equilibrium at every moment is approached by this mechanism. We must consider the couples \(M_L\) and \(M_G\) which are exerted by the air pressure and the weight \(G\) respectively on the shaft \(A\). It follows from equation (2) that:

\[
M_L = \frac{q^2 P_1}{v_1} \cdot x, \quad (3)
\]

where \(k\) is the perpendicular distance between the driving rod \(D\) and the shaft \(A\) (in the case of an adiabatic pressure alternation \(M_L\) is simply multiplied by a factor \(n = 1.4\)). When we call the angles \(\alpha\) and \(\beta\) through which the slotted bar \(K\) and the lever \(H\) respectively are turned, then

\[
M_G = n \cdot G \cdot h \cdot \sin \beta,
\]

and when we take into account the relations:

\[
\tan \alpha = \frac{x}{k},
\]

it follows that:

\[
M_G = n \cdot G \cdot h \sin \left(\frac{n \cdot \tan^{-1} \frac{x}{k}}{1.5}\right). \quad (4)
\]

In table I the data necessary for the calculation will be found. In fig. 5 the couples \(M_L\) and \(M_G\) calculated from (3) and (4) are plotted as functions of \(x\) for different values of the parameter \(h\). It may be seen that by a suitable choice of \(h\), the position of the moving weight \(G\), the curve \(M_G\) can be made to coincide almost exactly with the curve \(M_L\) at small values of \(x\). Only in the most extreme positions of the bellows (\(x > 20\) cm) does the shape of the two curves remain very different. In practice, however, no greater stroke \(s\) of the bellows is required than about 18 cm (corresponding to a difference in pressure of 0.2 atmospheres, with isothermal variation). The optimum position of the weight \(G\) depends upon the
necessary stroke. At \( s = 18 \) cm, for example, \( h \) would have to be taken equal to about 23 cm in the case of isothermal variations. The personnel in charge can determine the optimum position of the weight most easily by experiment.

It must still be noted that respiration with the "iron lung" can take place in different ways: the pressure in the chamber can be alternated between normal pressure and a lower pressure; or it may be made alternately higher and lower than normal. In the first case force is only used for the inspiration, in the second case for in- and expiration. In the foregoing and in fig. 5 we have assumed the first case. If the physician chooses the second method, the lever \( H \) bearing the counter weight \( Q \) is set at a different angle, so that it becomes vertical when the bellows are in the middle of the full stroke. The curves for the balancing in fig. 5 are then prolonged symmetrically for negative values of \( x \).

For working the apparatus by hand a long lever

3) In the first case, where the pressure in the chamber must never be higher than the external pressure, this is guaranteed in a simple way by means of a valve on the top of the chamber which allows air to escape when there is an excess pressure in the chamber. In working according to the second method this valve is fixed.

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Fig. 5. The couples \( M_L \) and \( M_C \) exerted by the air pressure and the counter weight respectively on the shaft \( A \) should be exactly equal for each position \( x \) of the bellows in an ideal case. The actual curves of \( M_L \) and \( M_C \) coincide fairly well when the stroke of the bellows is not too large (when, for instance, \( x < 18 \) cm), and when for the parameter \( h \) (position of the sliding weight \( G \) in fig. 4) a suitable value is chosen which is adapted to the stroke. \( M_L \) is here shown for both adiabatic and isothermal pressure variations. The actual curve will lie between these two.

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Fig. 6. The "iron lung" worked by hand. The person moving the handle can read off on the manometer the magnitude of the pressure alternations, and regulate the motion accordingly.
with a handle is attached to the end of shaft C, see fig. 6. The person moving the handle can read off on a manometer the magnitude of the pressure changes, and regulate the motion accordingly.

**Further details of the construction**

The chamber must be strongly built since it must resist large forces (several tons) during the pressure changes. It is welded from 1.5 mm steel sheet. Steel reinforcements have been entirely avoided on the inside in order to have smooth walls which can easily be cleaned. The chamber is mounted on four rubber wheels and is thus easily moved about. It is so narrow that it can pass through a door 90 cm wide. The bellows are connected by means of a flexible tube with the chamber, and together with the driving mechanism rest upon pieces of rubber so that any vibrations of the mechanical parts are not transmitted to the chamber. The body of the patient is introduced through an opening into the chamber. This opening is then closed with a cover (see fig. 1). Instead of one adult patient, two children can be treated at once in the apparatus. For this purpose two beds are placed end to end in the chamber and there is an opening for the patient's head at both ends. In the treatment of the patients great value is attached to the possibility of placing them in the so-called von Trendelenburg position, i.e. sloping, with the head low. A better drainage of saliva is hereby guaranteed and choking prevented and thus the occurrence of complicating inflammations of the lungs. The two beds can therefore be given a slope of 20° by means of the hand wheel visible in fig. 3. For an adult the two beds are coupled together to give a single bed which can be given a slope of 15°.

It is obvious that the chamber must be air-tight in order to obtain the necessary pressure alternations. Since the patient's head must remain outside the chamber, an air-tight seal is necessary around his neck. This is achieved by means of a collar whose construction is shown in fig. 7. The two thin rubber rings I have a slightly smaller diameter than the neck, and the edge of one is stretched upward and that of the other downward along the neck so that the seal is satisfactory for lowered as well as for excess pressure, without any discomfort to the patient. The leather supporting rings 2 are provided with four radial slide fasteners which are opened for the easy insertion of the head into the collar. The collar is not fixed in a permanent position in the cover of the chamber but it can be adjusted in any desired position by means of screws which slide in grooves. This may clearly be seen in fig. 8. The patient can therefore for example be laid on his side without it being necessary to turn his neck in the rubber rings.

The door which permits entry into the chamber is also sealed with rubber. Leaving or entering the

FIG. 7. The patient's head rests on a cushion supported by two iron bolts. When the patient's bed is made to slope (von Trendelenburg position) the cushion is suspended between two lower bolts. The nurse inside the chamber can see the patient's face through a window. Above the patient's head is a turning mirror in order to give the convalescent patient more contact with the outside world.
chamber costs the patient only two to three respirations. The nurse experiences no discomfort at all from the alternations of pressure in the chamber, the only sensation is a feeling of slight “fluttering” of the ear drums, which is decreased by swallowing, and which can be combatted if desired by cotton in the ears.

Fig. 8. Construction of the collar for sealing off the air-tight chamber around the neck of the patient. P neck of the patient, 1 thin rubber rings, 2 chrome leather supporting rings with slide fasteners, 3 metal rings for clamping, with which the whole arrangement is fastened so that it can be rotated in the cover of the chamber which opens to the side.

In one place a “leak” has expressly been introduced into the chamber wall, namely a small circular opening which can be more or less closed with a slide (visible in fig. 6 above the nurse’s head). Fine regulation of the pressure alternations is hereby made possible, while by the successive escaping and sucking in of a small quantity of air, ventilation of the chamber is also obtained.

In order to control the working of the apparatus a signal lamp (visible on fig. 1) has been installed above the chamber, which is switched on and off in the rhythm of the respiration by a membrane moving under the influence of the pressure variations.

Through a window in the chamber (see fig. 8) the nurse can see the patient’s face while she is attending to his needs in the chamber. In order to give the convalescent patient more contact with his environment, a mirror is mounted above his head, which is fastened with a ball and socket joint in the wall of the chamber and which can be turned in all directions by the patient’s hands inside the chamber.

The effect of the “iron lung” can be made directly visible by recording the patient’s breathing. Fig. 9 is an example of such a record. The force of the “iron lung” is so great that it is practically impossible even for a healthy person to breathe in opposition to the “iron lung” by the use of his respiratory muscles. This is clearly shown in fig. 9.

Fig. 9. Record of breathing in the “iron lung”. The lower strip gives the strokes of the “iron lung”, i.e. the movement back and forth of the driving rod of the bellows. On the upper strip the amount of air is registered which is sucked in and breathed out through the patient’s mouth. On the left may be seen how the respiration of the “patient” (a healthy person was used for this test) takes place in the rhythm of the “iron lung”. At A the patient tried to breathe in against the force of the “iron lung”. This was found to be practically impossible: the patient can at the most hold the breath in to some extent and in this way skip a stroke of the “iron lung”. Even this cannot be done for very long. At B the patient gives up the attempt, and gives himself up to the breathing of the “iron lung” again. At C the “iron lung” was stopped, and it may be seen that the patient now continues to breathe at his own slower rate and with less depth.