A NEW APPROACH TO ARTIFICIAL EXPANSION AND VENTILATION OF THE LUNG IN THE SEVERELY ASPHYXIATED NEONATE

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SUMMARY
In severe asphyxia, expansion of the newborn lung must precede ventilation by intermittent positive pressure. Inadequate expansion may lead to hypoxia and excessive expansion to rupture of the lung. The only way in which a predetermined pressure can be achieved, and not exceeded in the alveoli, is by applying that pressure at the mouth and waiting until all flow ceases. Applying pressure in this way and increasing it according to a "staircase" pattern, with appropriate steps at suitable intervals, should ensure that the maximum pressure produced in the alveoli is no greater than the minimum necessary for resuscitation in each individual infant. On the basis of published work, ranges of optimum values for the increments and time intervals are suggested. Clinical judgement is still necessary to select from within these ranges, but this "pressure staircase" method should provide a systematic approach to the problem. A suitable apparatus is described.
to allow a minimum of gas exchange. If that pressure is exceeded the lung may be damaged. Although expansion and rupture depend on the pressure in the alveoli, it is only the pressure at the mouth which can be controlled directly. Therefore, it is essential to consider those factors relating the pressure in the lungs to the pressure applied at the mouth.

When a fixed pressure is applied at the mouth, the pressure in the alveoli increases towards the applied pressure in an approximately exponential manner. The rate of increase of pressure depends on the time constant of the respiratory system which is equal to the product of total compliance and total respiratory resistance. Therefore, the peak pressure reached in the alveoli depends upon the pressure applied at the mouth, the time for which it is applied, and the time constant of the respiratory system. It is easy to determine the applied pressure and the duration of its application, but impossible to know the time constant. Time constants are different for each infant, change as expansion proceeds and vary from one part of the lung to another. Therefore, to apply a known pressure, of about 4 kPa, for an approximately known short time, 0.15 s or less (as suggested by Day and colleagues (1952)) may result in a very wide range of peak pressures in the alveoli of different infants and even in different parts of the same lung. As a result, some alveoli may be exposed to unsafe pressures while others are exposed to ineffective pressures. The only way to achieve a known pressure in all the alveoli is to apply that pressure at the mouth and to wait long enough for all flow to cease; then the applied pressure will exist throughout the lung. However, even when known pressures were applied in this manner, pressures which ruptured some excised human infant lungs failed to expand others fully (Rosen, Laurence and Mapleson, 1973). Furthermore, in some individuals the lungs ruptured even before full expansion. Therefore, those workers suggested that resuscitation might be achieved with much less than full expansion. Strong support for this proposition is provided by the findings of Vaughan and colleagues (1980) that severely asphyxiated lambs were resuscitated by a mean lung expansion of 6 ml kg⁻¹. This is only about one-third of the filling volume in the lamb (the volume at which the lungs appeared fully expanded) and only a quarter of the human neonatal lung filling volume (Rosen, Laurence and Mapleson, 1973). Nevertheless, in some individual lungs, the difference between the alveolar pressure which is just sufficient for resuscitation and that which causes rupture may be quite small. Therefore, it seems inappropriate to use a method of expansion which may produce a wide range of pressures in different parts of the same lung.

The method of choice must be to apply a known, safe pressure at the mouth for long enough to allow pressure equilibration throughout the lung. However, as the range of filling and rupture pressures between individuals is so wide (Rosen, Laurence and Mapleson, 1973) no single pressure can be selected to suit all neonates, nor is there any way of predicting the pressure necessary for a given individual. Therefore, it is essential to start by applying a small steady pressure at the mouth until the flow of inflating gas ceases and the applied pressure exists throughout the lungs. If there is no evidence of resuscitation, the mouth pressure should be increased progressively in a step-wise fashion, according to a “staircase” of pressure, until resuscitation occurs. The mouth pressure will nearly always have to be applied through an endotracheal tube to avoid inflating the stomach.

CHARACTERISTICS OF THE “PRESSURE STAIRCASE”

In practice several features of this “pressure staircase” have to be considered.

The initial pressure

In a study of 100 excised human infant lungs (Rosen, Laurence and Mapleson, 1973) it was found that, apart from one diseased lung which ruptured at 0.3 kPa, no ruptures occurred at less than 2.0 kPa. In a study of 36 severely hypoxic lambs (Vaughan et al., 1980) the smallest pressure which produced resuscitation in any lamb was 1.75 kPa. In the human infant study a pressure of 1.5 kPa filled to one-quarter capacity only one-third of the 100 lungs examined. Therefore, an initial pressure of 1.5–2 kPa seems reasonable.

The maximum pressure

There can be no maximum pressure. The pressure must be increased until resuscitation occurs or until it is evident that further attempts are useless. However, it is relevant that none of the 36 lambs required a pressure of more than 3.5 kPa for resuscitation, although a few of the 100 excised infant lungs required 5.0–6.0 kPa before becoming half full.
The magnitude of the incremental steps of pressure
Increasing the pressure by small increments decreases the risk of rupture, but increases the time taken to reach a pressure sufficient to expand the lungs and to resuscitate the infant, thus increasing the risk of hypoxic damage to the infant. The chosen size of the pressure increments depends upon the time available for resuscitation and the time interval needed between each of the increments in pressure. It seems likely from the previous studies that the size of the pressure increment should be between 0.25 and 1.0 kPa (Rosen, Laurence and Mapleson, 1973).

Time interval between pressure increments
In severe hypoxia there is a depression of cardiac output. As the lungs expand the pulmonary venous oxygen tension increases, but there is a delay before sufficient oxygen reaches the heart and cardiac output increases. In severely hypoxic lambs, 17–45 s elapsed between the first sign of increasing heart rate and full "resuscitation" (a pronounced increase in heart rate to a steady value) (Vaughan et al., 1980). No doubt this interval will depend upon the degree of circulatory depression present and either 15 s or 30 s might be a reasonable time interval between pressure steps. If the interval were 30 s and the pressure increments were 0.5 kPa, it would then take about 2 min to proceed from 1.5 to 3.0 kPa and another 3 min to attain 6 kPa. One possible routine would be to start at 1.5 kPa and apply increments of 0.5 kPa at 30-s intervals until the pressure reached 3.5 kPa, followed by increments of 1.0 kPa. An alternative routine, which would probably be equally effective and perhaps more acceptable to the anxious clinician, would be to use increments of 0.25 kPa at intervals of 15 s up to 3.5 kPa, followed by increments of 0.5 kPa. With this alternative routine some infants might be exposed to an additional unnecessary pressure step of 0.25 or 0.5 kPa. However, this would be balanced by others who would just reach the necessary resuscitation pressure 15 s earlier than with the 30-s interval routine. With either routine the person performing the resuscitation should use clinical judgement in deciding whether the severity or duration of the hypoxia in a particular case is such that the steps should be larger or more frequent than usual. Furthermore, heart rate should be monitored continuously to detect the first signs of resuscitation and thereby avoid any unnecessary pressure steps and possible rupture of the lungs.

The pressure must be maintained at least until pressure equilibrium is achieved throughout the lungs. The time required depends on the unknown time constant, but is most unlikely to exceed 5 s. If, as in the lamb experiments, the lungs are not allowed to deflate between increments until resuscitation is evident, such a time would be comfortably within any likely interval for each pressure step. Although it would probably not impair the expansion process, there seems little point in allowing deflation between pressure increments since, until expansion has occurred, there can be little effect on intrathoracic pressure and hence on venous return.

Artificial ventilation
Once resuscitation is evident, artificial ventilation should be instituted immediately. It would seem that no harm, and the maximum benefit, will occur if the pressure used is the maximum attained during the resuscitation procedure.

The mechanism for generating the pressures
It is not as easy as it may seem to arrange for a fixed pressure at the mouth which cannot be exceeded but which is close to some specified pressure. The use of a water blow-off valve seems attractive, but such valves have two practical drawbacks. They tend to be flow-dependent (Mathias, 1966; Hey and Lenney, 1973) and they have a "water-hammer" effect because of inertia of the water column which can result in a very high pressure being generated for a short time (fig. 1).

A suitable diaphragm valve (fig. 2) has been designed in Cardiff. (It is available from Cape Engineering Co. Ltd, Warwick CV34 5DL.) The pressure resulting from the use of this valve is largely independent of flow up to 50 litre min\(^{-1}\) and can be set in steps of 0.25 kPa up to 5.0 kPa, with a mechanical stop at 3.0 kPa. It blows off without reverberatory pressure (fig. 1b). There is a gauge in the system to check the applied pressure. This pressure-limiting valve is connected in the oxygen supply line to the T-piece used normally for inflation (fig. 3). To expand the lungs, the blow-off pressure is set to the desired initial value and the operator's finger is used to occlude the outlet of the T-piece. At intervals, the blow-off pressure is increased in accordance with the desired "staircase" until circulatory resuscitation is achieved. This method of expansion ensures...
largely that any leak around a tracheal tube has little effect, since the relatively high flow of oxygen keeps the pressure at the mouth constant. Furthermore, oxygen taken up by the lungs is replaced instantly, so that the pressure is maintained and the lung does not deflate, as would occur if a fixed volume were used for inflation. Once resuscitation of the circulation has been achieved, intermittent occlusion of the outlet of the T-piece produces intermittent positive pressure ventilation.
CONCLUSION

It must be emphasized that the above routine cannot ensure expansion of the lungs (still less, resuscitation) in every patient. This is almost certainly unattainable because of biological variation and other factors. Indeed, results in lambs (Vaughan et al., 1980) suggest that only about half of all the severely asphyxiated newborn might be resuscitated permanently and some of these might suffer neurological defects. Nevertheless, the present "pressure staircase" method represents, for the first time, a means by which the clinician can be sure that he will achieve expansion with the minimum necessary pressure. Clinical judgement is still required to make the actual choice of the initial and incremental pressures and times of application according to circumstances. These guidelines should make the decisions more effective.

ACKNOWLEDGEMENTS

We are grateful to the Welsh Office (Welsh Hospital Board) for a grant for the project.

REFERENCES

SUMARIO

En condiciones de asfixia grave, la expansión del pulmón del recién nacido debe preceder a la ventilación mediante presión positiva intermitente. La expansión inadecuada puede conducir a hipoxia y la excesiva expansión a la ruptura del pulmón. La única forma por la que puede lograrse la presión predeterminada y sin exceder esta, en el alveolo, es aplicando esta presión en la boca y esperando hasta que ofe todo flujo. El aplicar la presión de esta forma y el incrementaría siguiendo un modelo "escalando", con incrementos apropiados a intervalos adecuados, debiera garantizar que la máxima presión que se ejerce en el alveolo no es superior a la mínima necesaria para la resucitación de cada recién nacido. Se sugieren gamas de valores óptimos para los intervalos de los incrementos y del tiempo, en base al trabajo publicado. Es aún necesario el juicio clínico para seleccionar dentro de estas gamas, pero este método de "presión escalonada" debiera proveer un enfoque sistemático al problema. Se describe un aparato adecuado.