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.

Resuscitation of the apnoeic neonate requires ventilation of the lungs primarily. However, before the lungs can be ventilated they must be expanded and, in babies in whom there is no expectation of spontaneous expansion, this must be done artificially. The accepted method of artificially expanding the newborn lung is to apply positive pressure intermittently. However, such artificial expansion can lead to rupture of lung tissue since, when some lung units have almost reached their peak volume, further pressure may be required to open others (Radford, 1960; Strang, 1977).

The latest editions of important textbooks (Abramson, 1973; Avery and Fletcher, 1974) do not give any clear advice on exactly how this should be done. Pressures of 3–3.5 kPa for 1–2 s are mentioned (James and Apgar, 1973; Avery and Fletcher, 1974) as being needed. There is also reference to the work of Day and colleagues (1952) who showed that 4 kPa was safe in the expansion of atelectatic adult rat lungs, provided the pressure was applied for no more than 0.15 s. At the same time there is a claim (James, 1973) that reluctance to use pressures greater than 3 kPa is falsely based on data from the expansion of balloons and of lungs of infants with non-respiratory complications; there is a statement (Avery and Fletcher, 1974) that pressures of 5 kPa have been sustained in excised lungs of infants without leakage; there is also a reference (James and Apgar, 1973) to the finding of Karlberg and colleagues (1962) that infants produce negative pressures of 6–8 kPa during spontaneous expansions. Gruenwald, Strauss and Blanc (1973) think that infants whose lungs are predisposed to rupture cannot be saved by applying lower pressures; "they are doomed." Perhaps James (1973) best sums up current thinking by saying "We know that high pressure is necessary to achieve ... expansion. The best way to apply these pressures still has to be determined." Crawford (1978) feels that no currently available apparatus is satisfactory.

The moment when the clinician is faced with a severely asphyxiated newborn is not the time to start to determine that best way. On the basis of experimental and theoretical studies of excised lungs from human neonates (Rosen, Laurence and Mapleson, 1973) and of experimental studies of whole, deliberately asphyxiated, newborn lambs (Vaughan et al., 1980) we have devised a systematic approach to this problem.

RATIONALE

To resuscitate a baby, one must generate pressure great enough to produce lung expansion sufficient...
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. There-
fore, 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 applica-
tion, 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 approxi-
mately known short time, 0.15 s or less (as sug-
gested 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 indi-
viduals the lungs ruptured even before full ex-
ansion. Therefore, those workers suggested that
resuscitation might be achieved with much less
than full expansion. Strong support for this propo-
sition 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 re-
suscitation 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 stair-
case” 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 pres-
sure 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.
RESUSCITATION OF THE NEONATE

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.

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REFERENCES


NOUVEAU POINT DE VUE SUR L'EXPANSION ARTIFICIELLE ET LA VENTILATION DES POUMONS D'UN NOUVEAU-NE GRAVEMENT ASPHYXIE

RESUME

Dans les cas d'asphyxie grave, l'expansion des poumons du nouveau-né doit précéder la ventilation sous pression positive intermittente. Toute expansion inappropriée peut entraîner l'hypoxie et toute expansion excessive être à l'origine d'une rupture des poumons. La seule manière d'arriver à une pression prédéterminée, sans la dépasser dans les alvéoles, est d'appliquer cette pression à la bouche et d'attendre jusqu'à ce que le débit cesse. Le fait d'appliquer la pression de cette manière et de l'augmenter par paliers, avec des gradients appropriés et des intervalles convenables, devrait permettre de faire en sorte que la pression maximale produite dans les alvéoles ne soit pas plus forte que le minimum nécessaire pour la réanimation de chaque bébé. En se basant sur les travaux qui ont déjà été publiés, on suggère quelques plages de valeurs optimales pour les gradients et les intervalles de temps. Il est néanmoins toujours nécessaire d'appliquer un jugement clinique au moment de faire un choix parmi ces plages, mais cette méthode par paliers de pressions devrait permettre une approche systématique du problème. On décrit dans cet article un appareil approprié.

EIN NEUER WEG ZUR KÜNSTLICHEN EXPANSION UND BELÜFTUNG DER LUNGE BEI SCHWERER ASPHYXIA NEONATORUM

ZUSAMMENFASSUNG

NUEVO ENFOQUE A LA EXPANSION Y VENTILACION ARTIFICIAL DEL PULMON EN LOS RECIENTE NACIDOS CON GRAVE NIVEL DE ASFIXIA

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 ésta, en el alveolo, es aplicando esta presión en la boca y esperando hasta que cese todo flujo. El aplicar la presión de esta forma y el incrementarla 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.