PROPOSED UPPER LIMIT OF RESPIRATORY RESISTANCE FOR INHALATION APPARATUS USED IN LABOUR

M. I. J. HOGG, JUDITH M. DAVIES, W. W. MAPLESON AND M. ROSEN

SUMMARY
A specification for the upper limit of the inspiratory resistance for inhalation-analgesia apparatus used in labour has been derived by considering the additional respiratory power required to overcome the apparatus resistance. It is recommended that the additional power required to inspire through the apparatus, with the ventilation occurring in mothers having analgesia, should not be greater than the additional power involved in breathing without apparatus, at the greater ventilation found in mothers without analgesia. From data in the literature it is deduced that this general requirement will be satisfied for 99.9% of the population if the power dissipated in the apparatus is less than 1.68 watts at a ventilation of 40 l./min. This specific requirement is just met by a laminar-flow resistance of 0.26 cm H2O/(l./min). The Entonox apparatus and the Cardiff Penthrane Inhaler meet this requirement easily although they do not conform to British Standard Specification 4272, Part 2 (1968).

The British Standard specification for breathing apparatus used in labour (BS4272, Part 2, 1968) states the maximum permissible resistance of apparatus for the administration of nitrous oxide and oxygen for analgesia in labour. On inspiration the pressure drop must not exceed 5 cm H2O at a flow of 60 l./min and 15 cm H2O at 300 l./min. A subcommittee of the Medical Research Council apparently found this standard acceptable (Cole et al., 1970).

The Entonox apparatus does not meet these resistance requirements (Davies, Hogg and Rosen, 1974a) nor does at least one of the alternatives, the Cardiff Penthrane Inhaler (Jones, Molloy and Rosen, 1971). Yet artificially increasing the inspiratory resistance of both these apparatuses has been shown (Davies, Hogg and Rosen, 1974b) not to diminish the patient's ventilation until a high resistance is used; even then no mother rejects the apparatus. Consequently, it seems that the resistance of these present apparatus is not too great and that the British Standard specification is too stringent. An alternative specification for the inspiratory resistance of any apparatus used in inhalation analgesia during labour is here derived from considerations of the work and power of breathing.


Expiratory resistance is not considered here because it presents no practical problem (Davies, Hogg and Rosen, 1974a).

Theory.
It is important immediately to distinguish between work and power. To inhale and exhale one tidal volume requires a certain amount of work. To do so at a given frequency, that is, to maintain a given ventilation, requires a certain power or rate of work. Silverman and his colleagues (1945) and later Cooper (1961) suggested that a logical approach to determining acceptable values of apparatus resistance was to consider the increase in power required of the patient when breathing through the apparatus. If it could be shown that analgesia reduces the ventilatory response to the pain of uterine contraction it would follow that, in ventilating the lungs, less power is used than without analgesia; and the power saved could be used to overcome the resistance of inhalation apparatus. Crawford and Tunstall (1968) found, in the absence of analgesia and of inhalation apparatus, a mean ventilation during contractions of 42 l./min. With inhalation analgesia (and therefore with apparatus) Davies, Hogg and Rosen (1974b) found a mean ventilation during contractions of 18.8 l./min. That the decrease in ventilation was the result of the analgesia rather than the apparatus resistance was proved by the fact that deliberately increasing
the apparatus resistance further did not reduce ventilation further.

Thus analgesia does reduce the ventilatory response to uterine contractions and therefore we propose the following as a logical basis for determining the acceptable upper limit of the inspiratory resistance of apparatus for inhalation analgesia used in labour.

The resistance shall be such that the total power of breathing with the apparatus, at the ventilation which occurs with analgesia, shall be no greater than the power of breathing without the apparatus, at the ventilation which occurs without analgesia.

To derive a specification on this basis it is necessary to have not only data on ventilation in the two circumstances but also on the relation between ventilation and power dissipated in the lungs and in the apparatus.

METHOD

Data relating the power dissipated in the lungs to the ventilation are not available for pregnant women, so data for fit male volunteers were used (McIlroy, Marshall and Christie, 1954; Cooper 1961). Figure 1 shows these results and the regression line which was used to estimate the power dissipated in the lungs at any ventilation. The mean ventilation, during contractions, of mothers receiving inhalation analgesia during active labour (Davies, Hogg and Rosen, 1974b) was 18.8 l./min which requires a power dissipation in the lungs of 0.146 watt (fig. 1). In mothers in labour receiving no analgesia the mean ventilation during contractions was 42 l./min (Crawford and Tunstall, 1968) which requires a power of 0.6 watt. The difference between these two powers, 0.6—0.146=0.454 watt, could be used in overcoming respiratory resistance at 18.8 l./min ventilation.

However, inhalation apparatus must be suitable for most of the population and not only for the average patient. Therefore, an estimate of the highest likely ventilation is required. In the study of Davies, Hogg and Rosen (1974b) the standard deviation of ventilation through the apparatus was 7.0 l./min, and this is similar to that obtained in an earlier study (Major, Rosen and Mushin, 1967). Adding three standard deviations to the mean of 18.8 l./min gives an estimated upper limit of ventilation of 39.8 l./min which is likely to include 99.9% of the population. At this ventilation the power dissipated in the lungs would be 0.546 watt. Crawford and Tunstall (1968) do not provide enough information to allow calculation of the standard deviation of the ventilation of their patients. We assume that it is the same percentage of the mean as given above (37%). Adding three such standard deviations to the mean of 42 l./min gives a ventilation of 88.6 l./min at which the power dissipated in the lungs would be 2.227 watts. The difference between the two powers 2.227—0.546=1.681 watts, could be used in overcoming respiratory apparatus resistance at 39.8 l./min ventilation.

RESULTS

On the basis of the above estimates of ventilation and power the following specific requirement is proposed.

The resistance of any apparatus for inhalation analgesia in labour shall be such that at a ventilation
of 40 l./min the power dissipated in it shall be less than 1.68 watts.

In figure 2 the laminar-flow resistance which just satisfies this requirement (see Appendix) is compared with the British Standard specification and with the pressure-flow characteristics of the Entonox apparatus and the Cardiff Penthrane Inhaler. It is clear that neither apparatus meets the British Standard specification but that both easily satisfy the proposed requirement.

The laminar-flow resistance in figure 2 is only one of many resistances which will just satisfy the proposed requirement. For instance, an apparatus which exhibits a larger pressure drop at low flows can still satisfy the requirement if it exhibits sufficiently smaller pressure drops at high flows. This is because, comparing such an apparatus with the laminar-flow case, more work will be done at the low flows at the beginning and end of inspiration and less work at the high flows in the middle of inspiration.

In general, to determine if any particular apparatus conforms to the proposed requirements, either direct power measurements must be made, or else the pressure-flow characteristics must be measured, and the mean power dissipated in the apparatus at a ventilation of 40 l./min must then be calculated. If the result is less than 1.68 watts the apparatus satisfies the requirement. To help avoid the need for this calculation a number of pressure-flow characteristics have been calculated (fig. 3), any of which just satisfies the requirements. (The curves have been drawn only up to 125 l./min because this is about the highest instantaneous flow that will occur with a ventilation of 40 l./min—see Appendix.) Therefore, if the pressure-flow characteristic of an apparatus falls entirely below any one of the curves in figure 3, it will satisfy the proposed requirement.

DISCUSSION

It seems likely that the British Standard specification was designed to provide an acceptable pressure difference across the apparatus during inspiration at the highest flows found by Crawford and Tunstall (1968), presumably to avoid the apparatus being discarded by the mother. This does not appear to be necessary since mothers seem able to tolerate resistances even greater than that of the equipment in current use (Davies, Hogg and Rosen, 1974b).
In fact, with analgesia, the incidence of high peak flows is reduced (Davies, Hogg and Rosen, 1974b). Furthermore, high additional resistances eliminated these extremes of peak flow completely, yet there was no rejection by the mothers.

No allowance has been made for the power dissipated in the chest wall since the evidence concerning its magnitude seems to be inconsistent (Otis, 1964; McIlroy, Tierney and Nadel, 1963). However, if an allowance were made, this would further increase the amount of power available for overcoming apparatus resistance. Therefore, the proposed requirement is more stringent than strictly necessary.

Finally, hyperventilation may have undesirable consequences (Fadl and Utting, 1969) which might occur more frequently if the apparatus resistance were very low. Studies are planned to determine whether a lower limit of resistance need be defined also.

**APPENDIX**

Assume (Cooper, 1961) that respiratory flow varies sinusoidally, that only inspiration occurs through the apparatus, and that the pressure-flow relationship of the apparatus can be expressed by

\[ P = k \dot{V}^n \]  

where \( P \) = pressure difference, \( \dot{V} \) = flow and \( k \) and \( n \) are constants. The power \( W \) dissipated in the resistance is related to the ventilation \( \dot{V}_R \) by the equation

\[ W = \frac{k\pi^n}{2} \dot{V}_R^{n+1} \int_0^\pi \sin^{n+1} \theta \, d\theta \]  

(2)

Given an available power at a given ventilation, as in the proposed requirement, equation (2) can be solved for \( k \) for any value of \( n \) and the resulting pressure-flow characteristic plotted according to equation (1) (fig. 3). This should be done for flows up to the peak inspiratory flow which, for sinusoidal flow, is \( \dot{V}_R \).

Equations (1) and (2) are valid for any coherent system of units, such as SI units, but in the caption to figure 3, \( P \) and \( \dot{V} \) are given in conventional units, cm H₂O and l./min respectively.

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**REFERENCES**


