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THE ELIMINATION OF REBREATHING IN VARIOUS SEMI-CLOSED ANAESTHETIC SYSTEMS

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INTRODUCTION

A VALUABLE theoretical and experimental analysis of the flow of gases in a semi-closed anaesthetic system was published by Molyneux and Pask in 1951. Their theoretical analysis was applied to one particular type of system and involved the assumption of certain idealized characteristics of the expiratory valve and of the breathing pattern. In the present work it is proposed to extend the theoretical analysis to other types of semi-closed systems and to take account of the effects of the actual characteristics of the expiratory valve and reservoir bag and of breathing patterns other than the idealized one.

In all, five systems will be considered (A, B, C, D, E in figure 1) of which A was analyzed by Molyneux and Pask.

SYSTEM A

Expiratory valve close to face mask, separated by corrugated tube from reservoir bag and supply of fresh gases.

In this simple analysis the following assumptions will be made:

(1) Gas enters the system from the anaesthetic machine at a constant volume flowrate F_s.

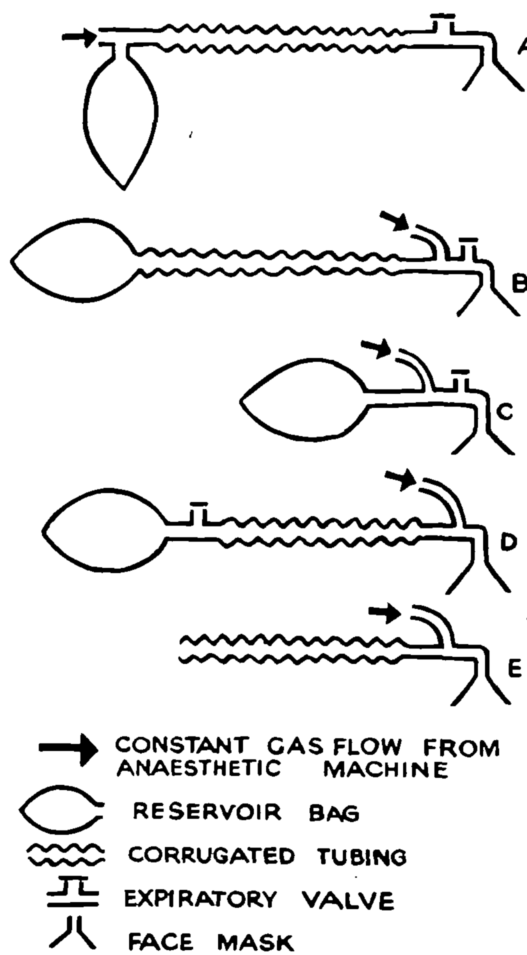

FIG. 1

The five semi-closed anaesthetic systems.

(2) At the start of inspiration the flow-rate into the lungs rises instantaneously to some value greater than F_a. No other assumption need be made as to the nature of the breathing pattern.

(3) The expiratory valve opens when the pressure in the system exceeds some critical value slightly above atmospheric and the valve will pass large flows without further increase in the pressure drop across it.

(4) The system is in a stable state—that is to say the conditions at any particular moment in the cycle of respiration are constant from one respiration to another.

(5) "Plug" flow occurs in the corrugated tubing, face mask and patient's trachea—that is, no longitudinal mixing occurs in these regions.

During expiration gases will enter the system at a known constant rate, F_a, from the anaesthetic machine and an unknown varying rate, say f_r, from the patient. Initially the fresh anaesthetic gases will flow directly into the bag while the expired gases will flow back along the corrugated tubing, forcing gas from the tubing into the bag. When the bag volume rises to some critical value, say V_o, at which the pressure inside it is equal to the opening pressure of the expiratory valve, the valve will open. Then, in virtue of assumption 3, the pressure in the system will not rise further and the volume of the bag will remain constant at V_o. The expired gases will flow directly out through the valve at an unknown varying rate which may still be represented by f_r, while the fresh anaesthetic gases will flow forward along the corrugated tubing still at the known constant rate F_a, forcing out through the expiratory valve gas which had previously entered the corrugated tube from the patient at the beginning of expiration. Apart from the variation of f_r conditions will then remain constant until the start of inspiration.

At the start of inspiration, in virtue of assumption 2, gas will be drawn from the system by the patient faster than it enters from the anaesthetic machine. The additional gas must necessarily be drawn from the reservoir bag whose volume will therefore decrease. Immediately this volume reduction starts there will be a corresponding reduction in the pressure in the system (Mapleson, 1954) below the opening pressure of the expiratory valve which will consequently close immediately inspiration begins. Thereafter conditions will remain steady, the bag slowly emptying, until the rate of inspiration, f_r, falls below the rate of supply of fresh gases, F_a, when the bag will begin to refill. When expiration commences the bag will fill comparatively rapidly in the manner described at the beginning of this analysis.

Now let V_t = patient's tidal volume.

T_1 = time from the start of one inspiration to the end of the same inspiration.

T_2 = time from the end of one inspiration to the start of the next inspiration.

T = duration of one complete respiratory cycle = $T_1 + T_2$.

T' = time from the end of inspiration to the opening of the expiratory valve.

Then the volume drawn from the bag during inspiration will be $V_t - F_a T_1$.

This volume is replaced during expiration in a time, T'. A portion, $F_a T'$, will come direct from the anaesthetic machine, while the remainder, $V_t - F_a T_1 - F_a T'$, will come from the patient. This last volume, $V_t - F_a T_1 - F_a T'$, is thus the volume of expired gas which enters the corrugated tubing and, at the instant at which the valve opens, will reside in the right-hand end of the tube (fig. 1, A), assuming, as one reasonably may in all normal circumstances, that this volume is less than the volume of the corrugated tubing. During the remainder of the time $T_2 - T'$ before the next inspiration, a volume, $F_a T_2 - F_a T'$, of fresh anaesthetic gas will enter the corrugated tubing from the machine at the left (fig. 1, A) and drive out through the expiratory valve at the right an equal volume of the expired gases residing in the right-hand end of the tubing. At the start of the next inspiration, therefore, the volume of expired gas still remaining in the corrugated tubing will be $V_t - F_a T_1 - F_a T' - F_a T_2 + F_a T' = V_t - F_a T$. However, this volume will be composed of gas which was breathed out at the beginning of expiration. Therefore, provided this volume does not exceed V_s, the dead space of the patient plus mask, it will not contain any gas which has been in contact with the alveoli of the lungs—that is to say, it will not contain any "contaminated" gas. Thus a criterion for the elimination of rebreathing may be expressed mathematically by:

$$V_t - F_a T \leqslant V_s$$

or

$$F_a \geqslant (V_t - V_s)/T \quad \dots\dots\dots\dots (1)$$

Now V_t/T is one tidal volume divided by the period of one respiratory cycle and consequently is equal to the minute volume.* Similarly, $(V_t - V_s)/T$ may be referred to as the "effective" minute volume, since it is equal to the average rate of supply of fresh gases to the alveoli of the lungs. Then the criterion for the elimination of rebreathing may be expressed in words by:

> "The volume flowrate of anaesthetic mixture must be not less than the patient's effective minute volume."

It will be realized that this criterion is considerably at variance with that established by Molyneux and Pask. This is due, of course, to the different assumptions made in the present analysis. It is now proposed to examine the effect of various inaccuracies involved in some of these assumptions.

Assumption 5 clearly represents a highly idealized state of affairs; some longitudinal mixing is bound to occur in the system so that when equation (1) is just satisfied some "contaminated" expired gas will, in fact, still reside in the corrugated tubing at the beginning of inspiration and will consequently be rebreathed. In order to *ensure* the elimination of rebreathing, therefore, the criterion:

$$F_a \geqslant V_t/T \quad \dots\dots\dots\dots (2)$$

might be adopted. That is to say that the flow of fresh gas must be not less than the patient's actual minute volume. It imposes the condition that in the absence of mixing none of the gas from the previous expiration shall remain in the system at the start of inspiration. Since mixing will occur some small volume of expired gas will in

* Minute volume (F_m) = tidal volume (V_t) × number of respiratory cycles per minute (n). Now, $n = 1/T$ (T in minutes); therefore, $F_m = V_t/T$.

fact remain (an equal volume of fresh gas having escaped through the expiratory valve to maintain the balance) but it will probably consist mainly of gas which has not been in contact with the alveoli of the lungs. Molyneux and Pask took an even stricter condition: namely, that the volume of expired gas which *initially* flows back into the corrugated tube shall not exceed the total deadspace. That is to say

$$V_t - F_a(T_1 + T') \leqslant V_s$$

or $$F_a \geqslant (V_t - V_s) / (T_1 + T') \quad \text{.....(3)}$$

Even with this condition, however, it is still just possible that mixing would lead to some small amount of rebreathing. In the limit, therefore, it could be assumed that rebreathing will be completely eliminated only if no expired gas is allowed to enter the corrugated tube at any time. That is to say $V_t - F_a(T_1 + T') \leqslant O$ or, since in this condition T' must equal O

$$F_a \geqslant V_t/T \quad \text{..............(4)}$$

(If the periods of inspiration and expiration are equal this is equivalent to saying that the flow of fresh gases must be at least equal to twice the actual minute volume.) If no mixing occurred a graph of percentage rebreathing against the ratio F_a/F_m where F_m is the actual minute volume would appear somewhat as the solid line of figure 2. With mixing, the graph would be modified to something like that shown by the dotted line in the same figure. It would appear that the only way to determine the exact nature of the dotted line would be to perform rapid continuous gas analysis within the semi-closed system. Until this is done and until an acceptable minimum percentage of rebreathing is agreed, it seems that the choice of the condition to establish a criterion for the effective elimination of rebreathing is largely arbitrary. In the author's opinion, quite a small increase in the flow of fresh gases above the minimum required by equation (1) would probably be sufficient to reduce the amount of rebreathing to an acceptably low level.

Instead of making assumption 2, let account be taken of the measurements of Proctor and Hardy (1949), which show that with a patient inspiring against negligible resistance (which will be the case in these semi-closed systems) the inspiratory flowrate increases gradually (though rapidly), and not instantaneously, at the beginning of inspiration. Thus there will be some short period of duration, say T_3, at the beginning of inspiration during which the inspiratory flowrate will be less than the flow of fresh gas from the machine. During this period, therefore,

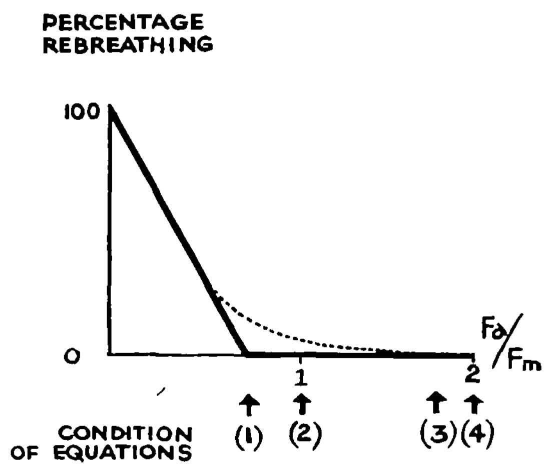

FIG. 2

Graph of percentage rebreathing against the ratio F_a/F_m (flowrate of fresh gases over patient's minute volume) for system A. Solid line: theoretical curve in the absence of longitudinal mixing. Broken line: assumed curve in the presence of mixing.

some of the gas in the right-hand end of the tube will enter the patient and some will leave through the expiratory valve. This state of affairs will persist until the inspiratory flowrate exceeds F_a when the valve will shut and the bag volume begin to decrease.

During this period a volume of gas, $F_a\ T_3$, will flow from the anaesthetic machine. If the rate of increase of inspiratory flow is constant during this period, half of this volume, namely $F_a\ T_3/2$, will enter the patient, and half will leave through the expiratory valve. Now during the remainder of the inspiration the patient will draw the remainder of the tidal volume, $V_t - F_a\ T_3/2$, and the anaesthetic machine will supply a volume, $F_a\,(T_1 - T_3)$ of fresh gas. The difference, $V_t - F_a T_1 + F_a T_3/2$, will be drawn from the bag. At a time T' after the end of inspiration, the bag will have regained its critical volume V_0, $F_a T'$ coming from the anaesthetic machine and the remainder, $V_t - F_a\,(T_1 - T_3/2 + T')$, coming from the patient's expiration (into the right-hand end of the corrugated tube). During the rest of the time up to the start of inspiration $(T_2 - T')$ a volume, $F_a\,(T_2 - T')$, of fresh gas will enter the left-hand end of the tube, driving out through the expiratory valve all but $V_t - F_a\,(T_1 - T_3/2 + T') - F_a\,(T_2 - T') = V_t - F_a\,(T - T_3/2)$ of the patient's expiration. Then, assuming that no longitudinal mixing occurs, it is this volume which must contain no "contaminated" expired gas if rebreathing is to be eliminated.

That is $V_t - F_a(T - T_3/2) \leqslant V_s$

or $F_a \geqslant (V_t - V_s)/(T - T_3/2)$.....(5)

From the graphs given by Proctor and Hardy it is apparent that, when F_a is about equal either to the effective or to the actual minute volume of the patient, T_3 is only about a tenth of T so that equation (5) differs only by a twentieth or a factor 1.05 from equation (1) and it is apparent that assumption 2 introduces no appreciable error.

Now let assumption 3 be modified to take account of the increase in pressure drop across the valve which occurs with an increase of flow through the valve (Mushin and Mapleson, 1954). Let the expiratory valve close at a time, T_4, after the start of inspiration and during this period let the patient inspire a volume, V_p. When the valve closes the bag volume will be V_0 and therefore at the end of inspiration it will be say, $V_1 = V_0 - \{V_t - V_p - F_a\,(T_1 - T_4)\}$. Let the bag volume at the beginning of inspiration be V_2. Then the net flow of expired gas into the corrugated tube will be $V_2 - V_1 - F_a\ T_2 = V - V_0 + V_t - V_p - F_a\,(T - T_4)$. This must be not greater than V_s for the elimination of rebreathing, in the absence of mixing. Therefore

$$F_a \geqslant \frac{V_t - V_s + (V_2 - V_0 - V_p)}{T - T_4} \quad .....(6)$$

In order to allot numerical values to the quantities $(V_2 - V_0 - V_p)$ and T_4 it is necessary to assume some definite shape for the respiratory flowrate curve and to apply a somewhat lengthy mathematical analysis which it is felt would be somewhat out of place here. However, it can be shown that under all conditions of respiration and valve and bag characteristics likely to be encountered in clinical practice the minimum value required for F_a in order to eliminate rebreathing while being, of course, greater than $(V_t - V_s)/T$ (the effective minute volume) will not be so great as V_t/T (the actual minute volume).

Assumptions 1 and 4 merely restrict the applicability of the analysis to steady conditions.

Thus it seems probable that the errors introduced by assumptions 2, 3 and 5 could be allowed for by adopting equation 2 rather than equation 1. That is to say that it is probably safe to assume that in system A rebreathing of gas which has been in contact with the alveoli of the lungs will be almost completely prevented if the flow of fresh anaesthetic gas is at least equal to the patient's minute volume.

SYSTEM B

Expiratory valve and supply of fresh gases close to face mask, separated by corrugated tube from reservoir bag.

The same assumptions will be made here as for system A. Some time during expiration the bag will fill to the critical volume V_0, and the expiratory valve will open, fresh gas passing directly out at a rate F_a and expired gas at f_r. At the start of inspiration the valve will close and gas will enter the patient at a rate F_a from the machine and a rate $f_r - F_a$ from the corrugated tubing and bag until the full tidal volume V_t has been drawn. Then, at the start of expiration, fresh gas will flow at a rate F_a and expired gas at a rate f_r back along the corrugated tube until the bag volume again reaches V_0 and the valve again opens.

Now the volume drawn from the corrugated tube and bag during inspiration $= V_t - F_aT_1$. Of this, $F_a T'$ will be replaced by fresh gas and the remainder, $V_t - F_aT_1 - F_aT'$, by expired gas. This gas will remain in the corrugated tube until inspiration begins since, when the expiratory valve is open, the fresh gases will leave directly through it instead of displacing expired gas from the tube as in system A.

Thus the amount of gas which will be rebreathed is $V_t - F_a T_1 - F_a T'$. Since this rebreathed gas entered the corrugated tubing at the start of expiration, it may be assumed that the rebreathing of contaminated gas will be eliminated if

$$V_t - F_a T_1 - F_a T' \leqslant V_s$$

that is, if $F_a \geqslant (V_t - V_s)/(T_1 + T')$...(7)

Now unless some assumption is made as to the form of the expiratory flowrate curve, T' is indeterminate. However, it must be less than T_2 and therefore $T_1 + T'$ must be less than T. Thus to eliminate rebreathing the flow of gases from the anaesthetic machine must exceed some value which itself is appreciably greater than the patient's effective minute volume. Thus a higher flowrate is needed in this system than in system A.

As in system A, equation (7) holds good only on the assumption (No. 5) that no mixing occurs in the patient's trachea and the face mask. If mixing is assumed to occur there, then the volume of expired gas which is permitted to enter the corrugated tube must be more severely restricted and in the limit *no* expired gas can be permitted to enter it. That is to say, $V_t - F_a T_1 - F_a T' \leqslant O$. Since T' must now equal O,

$$F_a \geqslant V_t/T_1 \text{ ....(8)}$$

Remembering that V_t/T is the patient's minute volume and that the measurements of Proctor and Hardy (1949) have shown that the duration of inspiration (T_1) is usually rather less than half the respiratory period (T) it is evident that the flow of fresh gas must be at least rather more than twice the minute volume of the patient.

If assumption 2 is modified to take account of the fact that the expiratory valve will not close until some finite time, T_3, after the start of inspiration, then it can be shown that equation (7) is modified to

$$F_a \geqslant (V_t - V_s)/(T_1 + T' - T_3/2) \quad \ldots (9)$$

As in system A, however, this represents only a very small change in the criterion, since T_3 will be only about one-tenth of T.

It is more difficult to determine what will happen if assumption 3 is modified to take account of the increase in pressure drop across the valve which accompanies an increase in flow through it. After the valve has just opened the pressure in the system will increase as the flow through the valve increases and consequently the volume of the bag will increase. If the pressure-flowrate characteristic of the valve has a gentle slope (that is, large flows can be passed for small increases of pressure above the opening pressure) only a small extra volume, including some expired gas, will enter the bag. Depending on the nature of the breathing pattern, some of this volume may still reside in the corrugated tube at the start of inspiration and so be rebreathed. If, however, the characteristic has a steep slope an appreciable volume would enter the bag, and to prevent this containing any "contaminated" expired gas it would be necessary to ensure that the bag reached its maximum volume early in expiration, before the expiration contained any gas which had been in contact with the alveoli of the lungs. It can be shown that this can be achieved if the valve first opens very soon after the start of expiration—in other words, if the fresh gas supplied by the machine during inspiration is almost as large as the patient's tidal volume.

Thus when account is taken of the effect of the various errors introduced by assumptions 2, 3 and 5 it seems probable that rebreathing of contaminated gas will be almost, if not quite, eliminated provided that the supply of fresh gas is at least equal to twice the patient's minute volume.

SYSTEM C

Expiratory valve, supply of fresh gases and reservoir bag, all close to face mask. (No corrugated tube.)

From figure 1 it is apparent that system C can be regarded as a limiting case of either system A or B in which the length of the corrugated tubing has been reduced to zero. The flow conditions of system A will be seriously altered when the length of the corrugated tube approaches zero since it can then no longer act as a depot in which the early part of expiration can temporarily reside, to be driven out of the expiratory valve, later in the expiratory phase, by fresh gases. In system B, however, the tubing merely forms an extension of the reservoir bag so that the conditions for the elimination of rebreathing in system C are the same as those in system B. If, however, any rebreathing does occur, the way in which the concentration of carbon dioxide builds up in the inspired air may well be different since mixing of each expiration with the gas in the bag will occur more efficiently in this system than in system B.

SYSTEM D

Supply of fresh gases close to face mask, separated by corrugated tube from reservoir bag and expiratory valve.

In this system during expiration fresh gas and expired gas will flow together, backwards along the corrugated tube, initially into the bag and later, when the bag has attained its critical volume, V_o, out through the expiratory valve. During inspiration, fresh gas will flow directly to the patient at a rate F_a, the remainder of the patient's inspiratory requirements being drawn along the corrugated tube from the bag.

The conditions in this system are clearly rather different from those in the three systems already considered. Any expired gas which enters the corrugated tube and is subsequently inspired will undoubtedly have been in contact with the alveoli of the lungs since it was derived from the last part of expiration. Thus, for the complete elimination of rebreathing, *no* gas from the previous expiration must be allowed to enter the lungs. The only condition under which gas may be drawn from the corrugated tubing during inspiration is if between the end of expiration and the beginning of inspiration there is a pause of duration, say T'', during which a volume of fresh gas, $F_a T''$, will accumulate in the right-hand end of the corrugated tube.

Then this volume, plus that supplied by the anaesthetic machine, must be not less than the tidal volume.

That is $\quad F_a T'' + F_a T_1 \geqslant V_t$

or $\quad F_a \geqslant V_t/(T_1 + T'')$ ....(10)

Since T'' is rarely more than a small fraction of T, the period of the respiratory cycle, this condition is approximately the same as that given by equation (8). Here it will hold true whatever the nature of the expiratory flowrate pattern (since T'' may be put equal to O if necessary), but it may be rendered false by certain types of inspiratory flowrate patterns. If $T'' = O$ then no gas must be drawn from the corrugated tube during inspiration. If the inspiratory flowrate pattern is a perfect square wave, then the assumption made above ($F_a T_1 \geqslant V_t$ when $T'' = O$) is justified, since the inspiratory flowrate will be constant and not greater than F_a during inspiration. However, if for the same tidal volume the inspiratory flowrate pattern is at all "peaky" some small volume of gas will at some stage during inspiration be drawn from the corrugated tube to be replaced by an equal volume of fresh gas from the anaesthetic machine towards the end of inspiration. If there is an appreciable expiratory pause ($T'' \neq O$) there would probably be a sufficient volume of fresh gas in the right-hand end of the corrugated tube to act as a buffer against this effect.

In this system there is no need to make assumptions 2, 3 and 5. It can be stated that rebreathing will be eliminated, providing the inspiratory flowrate pattern is not too "peaky", if the supply of fresh gas is at least equal to some value slightly greater than twice the patient's minute volume.

SYSTEM E

Supply of fresh gases close to face mask. Open length of corrugated tube. No reservoir bag or expiratory valve.

The conditions in this system are little different from those in system D except that during inspiration some fresh air may be drawn into the left-hand end of the tube and during expiration both expired gases and fresh gas from the machine will pass backwards along the corrugated tube straight out into the air. Assuming that wide bore connectors and tubing are used, the resistance of the system is very low. Therefore, the inspiratory flowrate pattern will be appreciably "peaky", but there will be an appreciable expiratory pause (Proctor and Hardy, 1949) so that the conditions for the elimination of rebreathing will be approximately the same as in system D.

Another method of eliminating rebreathing in this system is to use a very short length of corrugated tube. Suppose there is a definite pause, of duration T'', between the end of expiration and the start of inspiration. Then a volume, $F_a T''$, of fresh anaesthetic gases will enter the corrugated tube during this time. If the volume of the tube is no greater than this, then no rebreathing can occur (assuming that the expired gases are swept away from the end of the tube by draughts). However, if advantage is taken of this fact, the anaesthetic mixture will be diluted by fresh air unless $F_a (T_1 + T'')$ is at least equal to V_t. That is to say, that the flow of fresh gases must be at least equal to about twice the patient's minute volume.

Thus, if there is an expiratory pause, rebreathing can be eliminated in this system by using a length of corrugated tubing whose volume is no greater than the product of the duration of the expiratory pause and the flowrate of fresh anaesthetic gases, but the anaesthetic mixture will then generally be diluted by fresh air. If it is desired to avoid this dilution as well as eliminate rebreathing, then the flowrate of fresh gases must be at least equal to twice the patient's minute volume and then the length of the corrugated tubing is of little consequence except from the point of view of resistance.

CONCLUSIONS

From these results it is apparent that system A has a marked advantage over the others from the point of view of economy of gases (assuming that it is desired to eliminate rebreathing). On the other hand, system E has a marked advantage over the others from the point of view of resistance to breathing—all the other systems involve the use of an expiratory valve which imposes an appreciable resistance to expiration, particularly when it is passing a large flow (Mapleson and Mushin, 1954) as it will be with the high flowrates of anaesthetic gases required to eliminate rebreathing in systems B, C, and D.

SUMMARY

The flow of gases in five different semi-closed anaesthetic systems is examined theoretically. The minimum flowrate of fresh anaesthetic gases required to eliminate rebreathing is determined in each case.

The results may be summarized by saying that rebreathing has probably been eliminated if the flow of fresh gases is at least equal to the patient's minute volume in system A (fig. 1) and at least equal to about twice the minute volume in systems B, C, D, and E. Rebreathing can also be eliminated in system E with a smaller flow of gas if there is an expiratory pause and if the volume of the corrugated tube is no greater than the product of the duration of this pause and the flowrate of fresh

anaesthetic gases, but then the anaesthetic mixture will generally be diluted with fresh air.

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LIST OF SYMBOLS USED

f_r = volume flowrate of gases to or from the patient.

F_a = volume flowrate of fresh gases from the anaesthetic machine.

F_m = patient's minute volume.

n = number of respiratory cycles per minute.

T = duration of one complete respiratory cycle = $T_1 + T_2$.

T_1 = time from the start of one inspiration to the end of the same inspiration.

T_2 = time from the end of one inspiration to the start of the next inspiration.

T_3 = duration of the period at the beginning of inspiration in which $f_r < F_a$.

T_4 = time from the start of inspiration to closure of the expiratory valve (when taking account of the real valve characteristic).

T' = time from the end of inspiration to the opening of the expiratory valve.

T'' = time from the end of one expiration to the start of the next inspiration (" expiratory pause ").

V_o = volume of reservoir bag when the pressure inside it is equal to the opening pressure of the expiratory valve.

V_1 = volume of reservoir bag at the end of inspiration.

V_2 = volume of reservoir bag at the beginning of inspiration (when taking account of the real valve characteristic).

V_p = volume inspired by the patient during the period T_4.

V_d = deadspace of patient plus face mask.

V_t = patient's tidal volume.

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