REBREATHING IN A T-PIECE: VOLUNTEER AND THEORETICAL STUDIES OF THE JACKSON-REES MODIFICATION OF AYRE'S T-PIECE DURING SPONTANEOUS RESPIRATION

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SUMMARY

The Jackson–Rees modification of Ayre's T-piece was examined experimentally and theoretically to see what effects the theoretical restrictions of Onchi, Hayashi and Ueyama (1957) (1 : 1 i : e ratio, zero deadspace volume) and the square-wave approximation of Mapleson (1958) may have had on the calculated critical fresh-gas flow rate necessary to prevent rebreathing of exhaled alveolar gases. In the experimental examination six conscious alert volunteers breathed through the system as the fresh-gas flow rate was varied in steps, and their ventilation was recorded at each value. Assuming that under rebreathing conditions a normal arterial Pco₂ is maintained by hyperventilation, this experimental situation is identical with one of the two considered theoretically by assuming sine-wave inspiratory and expiratory waveforms, zero longitudinal mixing in deadspace volumes and perfect mixing in the alveoli. Agreement between experimental and theoretical results justifies the assumptions made in the theoretical analysis and the results indicate that a fresh-gas flow rate of about twice the normal ventilation is necessary to eliminate rebreathing completely from the Jackson–Rees modification of Ayre's T-piece. The exact requirement depends on the deadspace/tidal volume (Vd/VT) and I : E ratios. The onset of hyperventilation at lower fresh-gas flow rates is gradual and, in spontaneous breathing with Vd/VT approximately equal to 40% and I : E ratio = 1 : 1.2, is only 10–20% at a fresh-gas flow rate of 1.5 times the normal ventilation.

Investigations into theoretical and experimental aspects of modifications of Ayre's T-piece, used for the administration of anaesthesia, far outnumber those of the simple T-piece itself. Mapleson (1954) listed five semi-closed anaesthetic systems, including two versions of the T-piece system (fig. 1), and deduced, theoretically, values of the fresh-gas flow rates necessary to prevent rebreathing of the expired alveolar gases. In system E, on the basis of certain assumptions about the respiratory waveform, the prediction was that a flow of fresh gases into the T-piece of at least twice the minute-volume ventilation was needed to prevent rebreathing.

There have since been two quantitative theoretical assessments of the rebreathing problem. Onchi, Hayashi and Ueyama (1957) carried out a careful theoretical analysis of sine-wave respiration through a T-piece alone, and a T-piece fitted with reservoir tubes of volumes equal to specified fractions of the tidal volume. They concluded that in order to eliminate rebreathing and air dilution a fresh-gas flow rate of twice the normal ventilation and a reservoir-limb volume of 20% of the tidal volume should be used. They also showed that if the fresh-gas flow rate were reduced below this critical value, the onset of rebreathing was gradual. However, this investigation was restricted to the specific case of an inspiratory : expiratory time (I : E) ratio of 1 : 1 and the unrealistic case of zero deadspace volume.

In 1958, assuming a square-wave respiratory pattern, Mapleson extended his mathematical analysis of system E to the case where rebreathing of exhaled alveolar gases did occur, and compared his findings with the experimental data of Woolmer and Lind (1954) and Inkster (1956), who used respiratory models to simulate the respiration of children and adults.

Mapleson's analysis allowed for variation of I : E ratio, deadspace volume and reservoir-limb volume...
and confirmed the gradual onset of rebreathing especially for a large deadspace volume to tidal volume ratio.

In addition to several respiratory-model investigations, clinical measurements on three spontaneously-breathing patients anaesthetized using the Jackson-Rees modification of Ayre's T-piece were made by Eger (1974) who reported no change in end-tidal $\text{P} \text{CO}_2$ or ventilation until the fresh-gas flow rate was reduced to less than 1.5 times the ventilation measured in the absence of rebreathing.

The Jackson-Rees modification of Ayre's T-piece, referred to as system F for brevity (fig. 1), is used extensively in paediatric anaesthesia and has recently been used in coaxial form in paediatric and adult anaesthesia (Bain and Spoerel, 1972). Further investigation of this system seemed desirable to see if, by avoiding the various unrealistic assumptions of Onchi, Hayashi and Ueyama (1957) and of Mapleson (1958), agreement could be obtained between theoretical and experimental assessments of the degree of rebreathing.

The present study may conveniently be considered in two sections. In the first, conscious alert volunteers breathed through the system while different fresh-gas flow rates were supplied to the system and their minute-volume ventilation was recorded.

In the second, a theoretical analysis of system F was carried out, assuming a respiratory pattern which was sine-wave in each phase but which had a variable $V : E$ ratio, and assuming various values of deadspace volume ($V_D$) and tidal volume ($V_T$).

**VOLUNTEER EXPERIMENTS**

**Apparatus**

The form of system F used is shown in figure 2. The Wright Respirometer was arranged to measure the expired ventilation. The pneumotachograph was used merely to record the ventilatory waveform.
Geometric apparatus deadspace proximal to the fresh gas inlet was 43 ml. The fresh-gas flow rate \( (VF) \) was measured using a Rotameter which, with the Wright Respirometer, had been calibrated against a standard dry-gas meter which had been checked against a new 1% wet-gas meter and found to agree to within 1%.

**Method**

Each volunteer held the disposable mouth-piece firmly in the mouth and wore a nose-clip to prevent leakage. Each volunteer was familiar with the apparatus and the studies being carried out, but was kept in ignorance of all measured values and recordings.

In order that the volunteers might remain alert and not be too aware of the apparatus and of their own breathing, they were encouraged to concentrate their attention on reading matter which was interesting but not exciting. For each volunteer the first measurement was the control ventilation \( V_0 \) (the ventilation at a fresh-gas flow rate known, as a result of preliminary investigations, to prevent rebreathing—about three times the normal ventilation). The fresh-gas flow rate was then decreased in steps. After each change it took up to 4 min for the volunteer's ventilation to stabilize. Therefore a delay of at least 4 min was allowed and then the ventilation was measured at least twice over 2-min intervals. Magnetic-tape and paper-chart recordings of the respiratory pattern were made also. The zero level for these recordings was dependent on the fresh-gas flow rate and had to be reset at each value.

As a check on the reproducibility of the results the control ventilation was measured at the end of the sequence on each volunteer. The absence of leaks was checked continually by visual inspection of the apparatus, by inspection of the recorded respiratory waveform and by repetition of the observation sequence.

**Results**

Figure 3 illustrates the respiratory waveforms of one of the volunteers at various values of fresh-gas flow-rate, and shows also sine-wave respiratory patterns corresponding to \( I : E \) ratios of 1:1 and 1:2. Figure 4 shows the results obtained for one volunteer on three separate occasions over a period of 9 days, and while these results typify those obtained, not all volunteers gave such reproducible results.

In order to simplify comparison between results from different volunteers, having different control ventilations, the values of fresh-gas flow rate \( VF \) and the corresponding minute-volume ventilation \( \dot{V} \) for each individual have been normalized by dividing them by the control ventilation \( V_0 \) for that individual.

Figure 5 summarizes the measurements made on all volunteers. All curves except one represent the
THEORETICAL ANALYSIS

Method

The respiratory pattern was assumed to be sine wave in inspiration and in expiration, but the ratio of inspiratory period: expiratory period (i:E ratio), could be of any value. In the breathing system a steady state was assumed to exist, with no longitudinal mixing in the reservoir tube or in the anatomical deadspace, but perfect mixing in the alveoli.

The inspired volume (VT) is then a mixture of fresh gas and gas from the T-piece reservoir tube, the ratio of these volumes depending on the fresh-gas flow rate (VF) and on the inspiratory flow waveform; and in a like manner the gas inspired from the reservoir tube is a mixture of previously expired alveolar gas and fresh gas, the ratio of these volumes being dependent on the fresh-gas flow rate and the expiratory flow waveform.

The volume of gas inspired from the reservoir tube and the fraction of that volume which was previously-expired alveolar gas were computed iteratively for set values of i:E ratio, deadspace volume, fresh-gas flow rate and tidal volume. From these data the volume of rebreathed alveolar gas was calculated and used in the steady-state equation for alveolar carbon dioxide (CO₂) excretion. This equation was then solved to calculate the ventilation needed to maintain constant the rate of CO₂ excretion and the alveolar CO₂ concentration. A detailed account of this analysis is given in the Appendix.

Results

Theoretical curves corresponding to various Vd/VT ratios and an i:E ratio of 1:1.2 are shown in figure 6, together with the mean of all the volunteer data.

DISCUSSION

Recordings of the respiratory waveform of the volunteers (fig. 3) indicated that a sine wave was not an unreasonable approximation to the respiratory waveform both in inspiration and in expiration, and that as hyperventilation, resulting from decreased values of fresh-gas flow rate, became more pronounced, the respiratory waveform became more nearly sinusoidal. In addition, in most cases the i:E ratio changed with the fresh-gas flow rate, tending to 1:1 as hyperventilation increased. For these reasons a sine-wave respiratory pattern with an i:E ratio of 1:1.2, the mean value obtained for all flow rates in all volunteers, was used for the theoretical predictions.

The respiratory waveform recordings also showed that in every case hyperventilation was achieved by an increase in tidal volume, the respiratory frequency remaining approximately constant throughout the measurement sequence.

Figure 5 shows that, having normalized the results, the scatter between individuals is fairly small apart from subjects P. D. and M. H. Only one successful experiment was completed with subject P. D. Subject M. H. was obese and perhaps compensated less thoroughly for the rebreathing (by hyperventilation) and therefore caused his alveolar Pco₂ to increase. Experiments with another, more obese, subject had to be abandoned because he became distressed at the lower values of fresh-gas flow rate.
Some differences between experiment and theory must be expected because in addition to making the assumptions stated, the theory did not take into account the following facts:

(1) The theoretical results have assumed a constant deadspace volume as ventilation increased: in practice there is some increase in deadspace volume with tidal volume (Grey, Grodins and Carter, 1956) so that there is an increase in the ratio $V_d/V_{to}$ as hyperventilation increases, where $V_{to}$ is the control tidal volume. This explains to some extent the crossing of the theoretical curves corresponding to different $V_d/V_{to}$ ratios at constant $I:E$ ratio by the mean experimental results in figure 6; agreement being best with the theoretical curve corresponding to $V_d/V_{to} = 30\%$ when ventilation is near normal, but with the curves corresponding to increasing $V_d/V_{to}$ ratios as hyperventilation increases.

(2) To cause hyperventilation the alveolar $P_{co_2}$ of the volunteers must have increased to a small extent. Such an increase denotes that the volunteer’s ventilation will be lower than the corresponding theoretical case calculated for constant alveolar $P_{co_2}$.

(3) The $I:E$ ratio and respiratory waveform of the volunteers changed slightly with hyperventilation. We have not carried out calculations for changes in respiratory waveform but figure 7 illustrates the theoretical effect of variation in $I:E$ ratio at constant $V_d/V_{to}$ ratio (40%). The tendency for the volunteers’ $I:E$ ratio to approach 1:1 means that better agreement between experimental and theoretical curves would be obtained if the variation of $I:E$ ratio with fresh-gas flow rate were also taken into account, for example, considering a 1:1 ratio instead of 1:1.2 at $\bar{V}_{f}/\bar{V}_{o} = 1.0$ in figure 7 would have the effect of reducing the theoretical result by 2% (0.03 in 1.5).

Since all these considerations produce changes in a direction to improve agreement between experiment and theory, it seems that the assumptions made in the theory are well justified.

Thus, experiment and theory are agreed in showing that rebreathing begins when the fresh-gas flow is reduced to about twice the control ventilation, roughly in agreement with the zero-deadspace sine-wave analysis (Onchi, Hayashi and Ueyama, 1957) and with the square-wave analysis (Mapleson, 1958). However, the onset of rebreathing is even more gradual than that predicted by the square-wave analysis and, at a fresh-gas flow rate of 1.5 times the control ventilation, ventilation is increased by only 10–20% (fig. 6). Although this is not quite in accord with the summary in his book (Eger, 1974) it is in good agreement with the detailed results in patients kindly made available to us by Dr Eger.

**CONCLUSIONS**

For spontaneously-breathing patients whose respiratory pattern is reasonably similar to that of our volunteers, a fresh-gas flow rate of at least twice the normal total ventilation (that occurring in the absence of rebreathing) is necessary to be sure of eliminating rebreathing completely from the Jackson-Rees modification of Ayre’s T-piece. However, if the patient compensates for any rebreathing by hyperventilation, and if a 10–20% increase in the patient’s ventilation is acceptable, the fresh-gas flow rate may be reduced to 1.5 times the normal total ventilation. It is likely that these conclusions are also applicable to systems D and E for spontaneous respiration. With different respiratory waveforms as may sometimes occur with spontaneous ventilation, and almost always with controlled ventilation, the results may be very different, as pointed out by Eger (1974).

**APPENDIX**

The respiratory waveform is illustrated in figure 8A. Flow ($V$) is assumed to vary sinusoidally with time ($t$) but with different periods in the inspiratory and expiratory phases, that is:

$$V = V_1 \sin \omega_1 t \quad \text{for } 0 \leq t \leq \phi T$$

$$V = V_2 \sin \omega_2 t \quad \text{for } \phi T \leq t \leq T$$

$V_1$ and $V_2$ are the peak inspiratory and expiratory flow rates; $\phi$ is the ratio of the inspiratory phase duration to the total respiratory period ($T$) and $\omega_1$ and $\omega_2$ are the apparent angular frequencies during inspiration and expiration respectively. By assuming that the tidal volume $V_{tr}$ is equal to...
It is assumed that there is no longitudinal mixing of gases in the anatomical and apparatus deadspace nor in the reservoir limb of the Y-piece but that there is perfect mixing in the alveoli.

It is convenient to define two critical times. The first, \( t_{c} \), is defined as that time after which gas being inspired does not reach the alveoli, but remains in the deadspace volume. Thus \( t_{c} \) marks the division (fig. 8b) between the effective part \( (V_{T} - V_{D}) \) of the tidal volume \( V_{T} \) and the deadspace part \( V_{D} \). It follows from (1) that

\[
V_{T} = \int_{0}^{\phi} V_{I} \sin \omega t \, dt = 2V_{I}/\omega \Omega
\]

and that

\[
V_{T} - V_{D} = \int_{0}^{\phi} V_{I} \sin \omega t \, dt = (V_{I}/\omega \Omega)(1 - \cos \omega t_{c})
\]

The second critical time, \( t_{f} \), is defined as the time at which the instantaneous inspiratory flow rate, after passing through its peak value, equals the steady fresh-gas flow rate (fig. 8c). Then if the fresh-gas flow rate \( V_{F} \) is expressed as a fraction \( F < 1 \) of the peak inspiratory flow rate \( V_{I} \), \( t_{f} \) is defined by

\[
V_{F} = FV_{I} = V_{I} \sin \omega t_{f}
\]

For \( t > t_{f} \) the fresh-gas flow rate exceeds the instantaneous inspiratory flow rate and no rebreathing can occur. By the definition of \( t_{c} \) gas inspired after \( t_{c} \) cannot reach the alveoli. Therefore interest is confined to the composition of the gas inspired only up to the effective critical time \( t_{e} \) where \( t_{e} \) is equal either to \( t_{c} \) or to \( t_{f} \) whichever is the smaller.

Up to time \( t_{e} \) the volume of gas \( D \) demanded by the patient (fig. 8d) is given by

\[
D = \int_{0}^{t_{e}} V_{I} \sin \omega t \, dt = (V_{I}/\omega \Omega)(1 - \cos \omega t_{e})
\]

The volume of fresh gas supplied \( S \) is given by

\[
S = FV_{I}t_{c}
\]

The deficit (demand — supply) is given, using (4), by

\[
\Delta = D - S = \frac{V_{I} - \cos \omega t_{c} - Fo \omega t_{c}}{2}
\]

If this deficit is zero or negative there will be no rebreathing, but if it is positive it will be made good from the volume of gas in the reservoir limb—gas which entered it at the end of the previous expiration and therefore includes some alveolar gas and some fresh gas. The volume of previously expired alveolar gas in \( \Delta \) is the volume of alveolar gas rebreathed.

Let \( t_{v} \) be some arbitrary time, measured backwards from the end of expiration. Then, in the last \( t_{v} \) of the expiratory phase the volume of fresh gas \( V_{F} \) entering the reservoir tube is given by

\[
V_{F} = FV_{I}t_{v}
\]
and the volume of exhaled gas (all alveolar gas in the last VT–VD of expiration) Ve is given by

\[ V_e = \int_0^t V_f \sin \omega t \, dt = (V_f / \omega)(1 - \cos \omega t_f) \]

(10)

*The volumes of fresh gas and expired gas corresponding to an arbitrary time \( t = t_f \) are illustrated in figure 8e.*

If \( t_e \) is chosen such that

\[ V_f + V_e = \Delta \]

(11)

then \( V_e \) is the volume of alveolar gas rebreathed from the reservoir tube. Then, using (8–11)

\[ FV_t t_f + \frac{V_e}{\omega}(1 - \cos \omega t_e t_f) = V_T \frac{1 - \cos \omega t_e t_f - F\text{CO}_1 t_f}{2} \]

\[ \frac{2V_t F\text{CO}_1 t_f + 2V_e (1 - \cos \omega t_e t_f)}{\omega} = V_T \frac{1 - \cos \omega t_e t_f - F\text{CO}_1 t_f}{2} \]

and, using (3) and (4),

\[ F\text{CO}_1 t_f - \cos \omega t_e t_f = -(F\text{CO}_1 t_f + \cos \omega t_e t_f) \]

(12)

For specified values of \( I : E \) ratio and \( V_D/V_T \) ratio, \( V_e \) can now be calculated as follows:

(a) determine \( t_e \) from (5),
(b) determine \( t_f \) from (6),
(c) set \( t_e \) equal to \( t_f \) or \( t_f \) whichever is the smaller,
(d) determine \( t_e \) from (12) by iteration,
(e) determine \( V_e \) from (10).

The rate of carbon dioxide excretion is equal to the product of the fractional alveolar carbon dioxide concentration and the alveolar ventilation:

\[ \frac{V_e \text{CO}_2}{F\text{CO}_2} = f(V_T - V_D - V_e) \]

where \( f \) is respiratory frequency.

If the ventilation does not alter in response to rebreathing but the alveolar carbon dioxide increases then, assuming that, in the long run, carbon dioxide excretion remains constant,

\[ F\text{CO}_1 f(V_T - V_D - V_e) = F\text{CO}_1 f(V_T - V_D) \]

where \( F\text{CO}_1 \) is the control alveolar \( \text{CO}_2 \) with no rebreathing. Therefore

\[ \frac{F\text{CO}_1}{F\text{CO}_2} = \frac{V_T - V_D}{V_T - V_D - V_e} \]

On the other hand, if ventilation responds to rebreathing (by increasing the tidal volume at constant frequency) sufficiently well for \( F\text{CO}_1 \) to remain constant then

\[ V_T - V_D - V_e = V_t_0 - V_D \]

where \( V_t_0 \) is the control tidal volume. Therefore

\[ \frac{V_T}{V_t_0} = 1 + \frac{V_e}{V_t_0} \]

(13)

However, the calculation of \( V_e \) requires a knowledge of \( V_t \). Therefore, all the steps (a) to (e) above must be included with (13) in an iterative loop until values of \( V_t \) and \( V_e \) which satisfy (13) to the desired degree of accuracy are obtained.

REFERENCES
bringt bei spontaner Atmung mit \( \text{Vd/Vt} \) von etwa 40% und einem \( 1 : E \)-Verhältnis von 1 : 1,2 nur 10-20% des Wertes, der bei einer Frischgas-Zufuhr von einer Geschwindigkeit gegeben ist, die eindeutig mal so hoch ist wie bei normaler Belüftung.

**SUMARIO**

Se examinó experimental y teóricamente la modificación Jackson–Rees de la pieza en T de Ayre para ver los efectos que pueden tener las restricciones teóricas de Onchi, Hayashi y Ueyama (1957) (1:1 en la relación de \( I : E \), volumen de espacio muerto cero) y la aproximación de onda cuadrada de Mapleson (1958) sobre el porcentaje de flujo de gas fresco crítico calculado, necesario para prevenir la re-aspiración de gases alveolares exhalados. En el examen experimental, seis voluntarios conscientes y despiertos respiraron a través del sistema conforme se varió en etapas el flujo de gas fresco y su ventilación se registró en cada valor. Suponiendo que, en condiciones de re-aspiración, se mantenga por hiperventilación un \( P\text{CO}_2 \) arterial normal, esta situación experimental es idéntica a una de las dos consideradas teóricamente, suponiendo que se obtienen ondas sinusoidales de inhalación y exhalación, una mezcla longitudinal nula en volúmenes de espacio muerto y una mezcla perfecta en los alveolos. La coincidencia entre los resultados teóricos y prácticos justifica lo supuesto en el análisis teórico y los resultados indican que se necesita un porcentaje de flujo de gas fresco de alrededor del doble de la ventilación normal para eliminar la re-aspiración completa de la modificación Jackson–Rees de la pieza en T de Ayre. Las necesidades exactas dependen de las relaciones \( I : E \) y \( \text{Vd/Vt} \) y del volumen variable/espacio muerto. El comienzo de la hiperventilación a porcentajes de flujo de gas fresco más bajo es gradual y en respiración espontánea con \( \text{Vd/Vt} \) es aproximadamente igual al 40% y la relación \( 1 : E = 1 : 1,2 \) es sólo del 10 al 20%, a un porcentaje de flujo de gas fresco de 1,5 veces la ventilación normal.