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Spontaneous Breathing with a T-Piece Circuit:

Minimum Fresh Gas/Minute Volume Ratio Which Prevents Rebreathing

Steven E. Dean, B.S.,* and Richard L. Keenan, M.D.†

Thirty adults undergoing elective superficial surgery under enflurane-nitrous oxide anesthesia while intubated and breathing spontaneously via a modified Mapleson D (Bain) T-piece circuit were studied with their consent. Total fresh gas flows which were initially high were adjusted downward until minimal rebreathing (inspired CO_2 tension of 5 to 10 mmHg) was present. At this point both fresh gas flow ($\dot{V}_F$) and minute volume ($\dot{V}_E$) were recorded, and the ratio of the two ($\dot{V}_F/\dot{V}_E$) was calculated. The mean $\dot{V}_F/\dot{V}_E$ ratio was found to be 1.89 ± 0.27 (SD).

Linear regression was used to plot $\dot{V}_F$ against $\dot{V}_E$, breathing frequency, tidal volume, age, weight, and end-tidal CO_2 tension. Significant correlation was found only with $\dot{V}_E$ ($r^2 = 0.48$, $P < 0.001$) and frequency ($r^2 = 0.44$, $P < 0.001$). When the ratio $\dot{V}_F/\dot{V}_E$ was plotted against the same variables, no significant correlation was found.

This study showed a wide variability in the minimum $\dot{V}_F/\dot{V}_E$ ratio which prevents rebreathing. The respiratory waveform, which was not studied, probably played a role in determining the $\dot{V}_F/\dot{V}_E$. Nevertheless, 87 per cent of our patients required a $\dot{V}_F/\dot{V}_E$ ratio of 2.0 or less to prevent rebreathing.

If one is especially concerned about rebreathing, $\dot{V}_E$ should be measured and the $\dot{V}_F$ adjusted to about twice the measured $\dot{V}_E$. **(Key words: Anesthetics, volatile; enflurane. Equipment: circuits; T-piece, Bain, Mapleson D. Ventilation: spontaneous; carbon dioxide, rebreathing.)**

IN 1954 MAPLESON PREDICTED that the fresh gas flow needed to eliminate rebreathing in his D type T-piece system would need to be "slightly greater than twice the patient's minute volume."[1] This was later confirmed in model studies by Inkster[2] and Harrison,[3] and in awake volunteers by Willis, Pender, and Mapleson.[4]

The introduction of the Bain circuit[5] renewed interest in the investigation of rebreathing during spontaneous ventilation. Several publications attest to the interest on the subject of rebreathing during spontaneous ventilation with this circuit.[6–10] Recommendations for fresh gas flows of 100 ml/kg by Bain[5] and Spoerel and Aitken[11] and 200–300 ml/kg by Rose, Byrick, and Froese[12] are examples of the extremes to be found in determining the gas flows during spontaneous ventilation with the Bain circuit. However, no study to date has looked specifically at the ratio of fresh gas flow to minute volume which is required to eliminate rebreathing during spontaneous ventilation in anesthetized patients. This study was designed to determine that ratio and the extent of its variability during enflurane anesthesia.

Methods

Thirty adult patients scheduled for elective surgery gave their informed consent for this study which was approved by the institution's Human Research Committee. Mean age of the subjects was 36.7 ± 13.4 (SD) years, and mean weight 77.7 ± 11.5 (SD) kg. Physical status was ASA 1 or 2; surgery consisted of orthopedic procedures of the knee in 28 patients, breast biopsy, and inquinal herniorrhaphy in one each.

One hour after intramuscular meperidine, hydroxyzine (1 mg/kg each), and 0.2 mg glycopyrrolate, anesthesia was induced with intravenous 3–4 mg/kg thiopental. A cuffed endotracheal tube was placed with the aid of 1.5 mg/kg succinylcholine. Maintenance was with enflurane in an inspired concentration of 2.0 to 2.5 per cent with 50 per cent nitrous oxide and oxygen delivered via a commercially available disposable adult Bain circuit. Ventilation was spontaneous and unassisted during the period of study.

A Wright respirometer was used to measure expired minute volume ($\dot{V}_E$) at the endotracheal tube. Its accuracy was previously verified by manually injecting between 0.5- and 1.0-liter aliquots of air from a calibrating syringe through the respirometer at a rate of approximately 0.5 l/s. Fresh gas flow rate ($\dot{V}_F$) was read from the flowmeters of an anesthesia machine which when tested with the Wright respirometer agreed within 0.5 l/min or less at total flows of 14 to 20 l/min. An infrared carbon dioxide analyzer (Cavitron® model PM-20R) calibrated with a known gas mixture of carbon dioxide in nitrogen recorded the CO_2 tension of respiratory gas sampled continuously at a rate of 150 ml/min at the endotracheal tube connector. Sample gas was not returned to the system. Recorded CO_2 tensions were not corrected for nitrous oxide interference. While spectral overlap has been eliminated in this instrument by the use of an optical filter, the "collision broadening" effect remains and would be expected to produce readings 5 to 10 per cent higher than actual.[13] For this reason nitrous oxide concentrations were held constant at 50 per cent during the period of study.

After anesthetic induction, and prior to the period of study, $\dot{V}_F$ was kept at a level high enough (generally in

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* Student in Nurse Anesthesia.

† Professor and Chairman.

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Address reprint requests to Dr. Keenan.

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TABLE 1. Means and Standard Deviations of Data Collected from 30 Patients

	Mean	SD
$\dot{V}_F$		
l/min	8.77	1.60
ml·kg^{-1}·min^{-1}	116.00	32.00
$\dot{V}_E$		
l/min	4.70	0.89
ml·kg^{-1}·min^{-1}	65.00	18.00
$\dot{V}_F/\dot{V}_E$	1.89	0.27
f	17.10	4.10
V_T (ml)	286.00	63.00
$P_{I_{CO_2}}$ (mmHg)	5.10	0.90
$P_{ET_{CO_2}}$ (mmHg)	56.70	7.80

excess of 10 l/min) to maintain an inspired CO_2 tension ($P_{I_{CO_2}}$) of zero, indicating no rebreathing. At least 20 min after skin incision, with the patient breathing spontaneously, $\dot{V}_F$ was decreased in 0.5 l/min steps at 5-min intervals. At the end of each interval end-tidal CO_2 tension ($P_{ET_{CO_2}}$), $P_{I_{CO_2}}$, and $\dot{V}_E$ were observed for one min. The $\dot{V}_F$ thus was decreased until $P_{I_{CO_2}}$ rose to between 5 and 10 mmHg, indicating the onset of rebreathing. In no case did $P_{ET_{CO_2}}$ or $\dot{V}_E$ change in response to the rise in $P_{I_{CO_2}}$, suggesting that the rebreathing observed at the endotracheal connector did not penetrate to the area of alveolocapillary gas exchange. $\dot{V}_E$ was determined for one minute during which time CO_2 tension was recorded at a paper speed of 15 mm/s. Respiratory frequency (f) was taken as the number of waveforms on the one-min tracing and tidal volume (V_T) was calculated by dividing $\dot{V}_E$ by f. $P_{I_{CO_2}}$ was determined by averaging the *highest* inspired tension recorded for each of the breaths during a minute; $P_{ET_{CO_2}}$ was similarly determined by using the highest expired tension.

In an attempt to identify those variables which might affect rebreathing, the data collected were analyzed statistically with single as well as multiple linear regression and correlation. The variables f, V_T, $\dot{V}_E$, $P_{ET_{CO_2}}$, body weight, and age were regressed against the observed $\dot{V}_F$ at which rebreathing began, and also against the observed $\dot{V}_F/\dot{V}_E$ ratio. Relationships were considered significant when *P* was less than 0.05. Coefficients of determination (r^2 for single, R^2 for multiple regression) are reported only where statistically significant relationships were found.

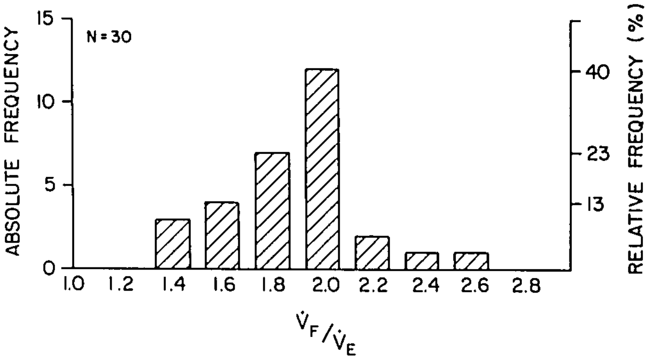

FIG. 1. Histogram of minimum $\dot{V}_F/\dot{V}_F$ ratios which prevented rebreathing with a Bain circuit in 30 patients breathing spontaneously under enflurane anesthesia. Frequency refers to number of patients observed at each ratio.

Results

Mean values of all measured variables from the 30 subjects are shown in table 1 with their standard deviations. The ratio $\dot{V}_F/\dot{V}_E$ was determined separately for each patient. The mean value for all patients was 1.89 ± 0.27 (SD). The histogram in figure 1 displays the variability of the ratio seen in this study.

Single linear regression analysis revealed a significant relationship of $\dot{V}_F$ to $\dot{V}_E$ ($r^2 = 0.48$, $P < 0.001$) which is shown in figure 2. The relationship of $\dot{V}_F$ to f was also significant ($r^2 = 0.44$, $P < 0.001$), but the relationship of $\dot{V}_F$ to the other variables was not. No significant relationship was found between the ratio $\dot{V}_F/\dot{V}_E$ and the variables f, V_T, $P_{ET_{CO_2}}$, body weight, and age.

Multiple linear regression of both $\dot{V}_E$ and f against $\dot{V}_F$ yielded a coefficient of determination (R^2) of 0.52 ($P < 0.001$). Addition of the other variables did not improve the correlation.

Discussion

The minimum fresh gas flow rates ($\dot{V}_F$) found to prevent rebreathing in our patients breathing spontaneously via a Bain circuit under enflurane anesthesia (mean $\dot{V}_F$ = 116 ml·kg^{-1}·min^{-1}) are comparable to those found by Spoerel, Aitken, and Bain[11] and by Byrick and Janssen.[8] Considerable variability among our subjects was seen, from a low $\dot{V}_F$ value of 71 to a high of 220 ml·kg^{-1}·min^{-1}. Of all measurements taken, minute volume ventilation ($\dot{V}_E$) correlated best with $\dot{V}_F$. About half the variability ($r^2 = 0.48$) of $\dot{V}_F$ required to prevent rebreathing could be accounted for by differences in $\dot{V}_E$. This is consistent with Mapleson's original and now widely accepted view[1] that it is the $\dot{V}_F$ in relation to $\dot{V}_E$ (that is, the ratio $\dot{V}_F/\dot{V}_E$) which largely determines the presence or absence of rebreathing in a T-piece system. The other half of the observed variability in this study remains unexplained.

Respiratory frequency (f) also correlated significantly with $\dot{V}_F$($r^2 = 0.44$). But, it is likely that f correlated with $\dot{V}_F$ through $\dot{V}_E$, since f is a determinant of $\dot{V}_E$. Multiple regression analysis of both f and $\dot{V}_E$ against the dependent variable $\dot{V}_F$ improved the correlation only slightly ($R^2 = 0.52$), suggesting that this was the case.

The principle finding of this study was that a minimum $\dot{V}_F$ of approximately twice the $\dot{V}_E$ (mean $\dot{V}_F/\dot{V}_E = 1.89$) is required to prevent rebreathing in a Mapleson D system during spontaneous ventilation under general anesthesia with enflurane. This is close to Mapleson's original theoretical prediction,[1] and similar to results of model studies[2,3] and findings from awake volunteers.[4] Such similarities imply that variables which control rebreathing in T-piece systems are similar in awake and anesthetized subjects.

The variability of the ratio $\dot{V}_F/\dot{V}_E$ was found to be wide, being as little as 1.4 and as great as 2.6 in individual patients (fig. 1). This too suggests that some factor or factors other than $\dot{V}_F$ and $\dot{V}_E$ play an important role in determining the presence of rebreathing in T-piece systems. However, none of the other variables observed in this study ($\dot{V}_T$, f, P_{ETCO_2}, age, and weight) showed a significant correlation with the $\dot{V}_F/\dot{V}_E$ ratio.

The unexplained variability in $\dot{V}_F$, and all the variability in $\dot{V}_F/\dot{V}_E$ is most likely due to differences in individual patient respiratory waveforms, which we did not measure or control. Theoretical studies by Mapleson[7] and by Willis, Pender, and Mapleson[4] predicted that changes in relative durations of inspiration and expiration would affect rebreathing. Harrison[3] found in his model studies that he could change the $\dot{V}_F/\dot{V}_E$ ratio which prevents rebreathing from 1.6 to 3.0 by varying the respiratory waveform, notably the expiratory time. Recently Byrick and Janssen[8] studied the effect of different waveforms on rebreathing during halothane and enflurane anesthesia. Although their results have been challenged because large differences in $\dot{V}_E$ were not taken into account,[9] they concluded that the respiratory waveform did affect rebreathing. Our findings are consistent with the view that the breathing pattern is an important factor in determining rebreathing in T-piece systems, second only to the relationship of $\dot{V}_F$ to $\dot{V}_E$. A wide variability in $\dot{V}_F/\dot{V}_E$ suggests that there is a wide variability in waveforms among individuals breathing spontaneously under enflurane anesthesia. To the extent that respiratory waveforms are unpredictable and not readily measurable clinically, it may be difficult to predict a minimum fresh gas flow which will prevent rebreathing for an individual patient any closer than "about twice the minute volume." Despite the wide variability, 26 of our 30 patients (87 per cent) had a $\dot{V}_F/\dot{V}_E$ of 2.0 or less (fig. 1), suggesting that rebreathing can be avoided in most cases at this level, and will be only modest in the remainder.

Can the results of this study be applied to anesthetic methods other than enflurane? We would predict that the mean $\dot{V}_F/\dot{V}_E$ ratio at which rebreathing begins is similar with all anesthetic techniques, since a ratio close to 2.0 has been found in theoretical and model studies, is true of awake subjects, and now has been seen in patients anesthetized with enflurane. Regarding $\dot{V}_F$ alone, however, our results cannot be applied to other conditions or agents. All of our patients had significant respiratory depression and CO_2 retention ($P_{ETCO_2} = 57$ mmHg) not from rebreathing, but from hypoventilation ($\dot{V}_E = 65$ ml/kg). An anesthetic technique which allows less depression and a higher $\dot{V}_E$ would require a higher $\dot{V}_F$ even if the ratio $\dot{V}_F/\dot{V}_E$ were unchanged. Using the ratio found in this study, one may calculate that during normal ventilation with a $\dot{V}_E$ of 80 ml/kg, rebreathing is prevented by a $\dot{V}_F$ of 150 ml·kg^{-1}·min^{-1} (80 × 1.89) in 50 per cent of subjects. It is interesting that Ungerer[10] found only a small amount of rebreathing in volunteers at this level of $\dot{V}_F$.

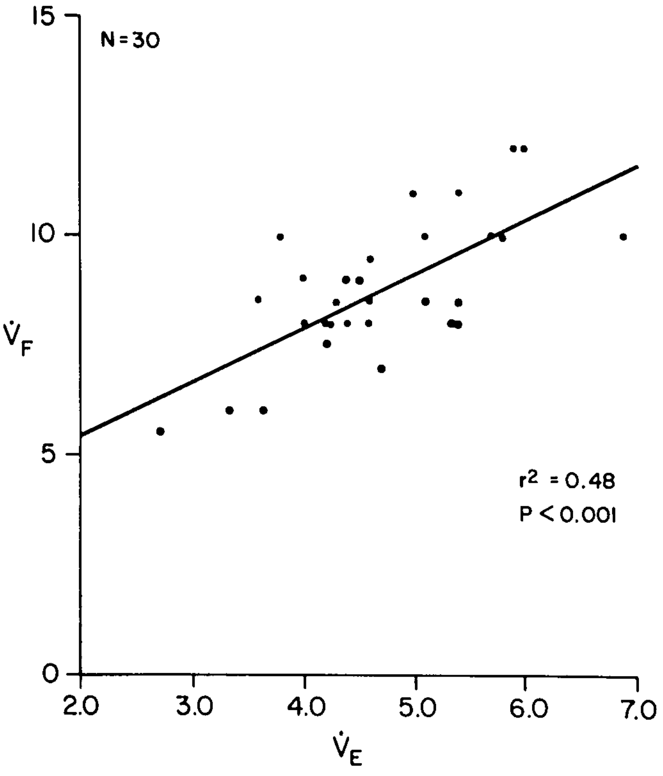

FIG. 2. Correlation of fresh gas flow ($\dot{V}_F$) required to prevent rebreathing with minute volume ($\dot{V}_E$).

The results of this study suggest that the recommendation of Spoerel, Aitken, and Bain[11] to use a $\dot{V}_F$ of 100 ml·kg^{-1}·min^{-1} during spontaneous ventilation, will result in rebreathing in some, but not all, anesthetized patients. We would predict little or no rebreathing at this $\dot{V}_F$ during enflurane anesthesia in which $\dot{V}_E$ is depressed, as Spoerel *et al.* found.[11] But significant rebreathing would be expected during halothane anesthesia with less depression and higher values of $\dot{V}_E$, as Byrick and Janssen have shown.[8] The recommendation of Rose, Byrick, and Froese,[12] however, that the $\dot{V}_F$ be set "between 200 and 300 ml·kg^{-1}·min^{-1} for an average adult," seems excessive and therefore wasteful in light of our findings. We suggest that if one considers rebreathing undesirable, the selection of $\dot{V}_F$ on the basis of body weight is inappropriate. Rather, the $\dot{V}_F$ selected for use with a Bain circuit during spontaneous ventilation should be based on actual measurement of $\dot{V}_E$ during anesthesia. If the $\dot{V}_F$ is then set at about twice the measured $\dot{V}_E$, rebreathing will be avoided totally in most patients, and will probably be only modest in the remainder.

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