PREDICTION OF INSPIRED OXYGEN CONCENTRATION WITHIN A CIRCLE ANAESTHETIC SYSTEM

J. A. RAYMOND

SUMMARY

Fresh gas flows of nitrous oxide, oxygen and halothane at 6, 3, 2 and 1 litre/min were introduced into a circle absorber system. Spontaneous respiration and IPPV were studied and a regression of inspired on delivered oxygen concentration % was calculated. The difference between delivered and inspired oxygen concentration % was increased by decreasing the fresh gas flow and by decreasing the proportion of oxygen in that flow, especially during IPPV. Circuits designed to allow a maximum overflow of alveolar gas provided a greater inspired oxygen concentration. The patients' height and weight were related to the scatter of inspired values observed at 1 litre/min of fresh gas flow with IPPV.

It has been stated that low fresh gas flows of nitrous oxide and oxygen are unsafe in a circle system with carbon dioxide absorber. The inspired oxygen concentration is reduced and may be difficult to predict. The author has studied the effect of a gradual reduction in fresh gas flow, and observed the gradual development of a discrepancy between the delivered and inspired oxygen percentage. Variations which might develop within or between different patients have been studied also. In addition it was hoped to consider the effect of circuit design on the inspired oxygen concentration. The difference between spontaneous respiration and IPPV was regarded as inseparable from the design factor.

The concentrations of gases within a circle are affected by the expiration of alveolar gas into the expiratory limb. A proportion of this gas, containing a reduced percentage of oxygen, will enter the inspiratory limb.

Eger and Ethans (1968) measured carbon dioxide input using a model, and studied the effect of different sites of inflow, overflow and valve placement on the economy of the circle system for carbon dioxide. A design which allows a maximum loss of alveolar gas containing carbon dioxide from the overflow valve will tend to maintain the oxygen concentration in the system.

During spontaneous respiration an overflow at the Y-piece (fig. 1) allows alveolar gas to be lost selectively through the overflow valve during late expiration. Any other siting allows mixing of alveolar gas in the circle before the overflow is reached. When mixing

has occurred, the overflow should be sited on the expiratory limb to conserve fresh gas. For IPPV the overflow should be sited distal to the expiratory unidirectional valve. Similar benefit is obtained if the unidirectional valves are at the Y-piece, the overflow being sited distal to these (fig. 8).

Small variations of oxygen concentration are produced because of the admixture of carbon dioxide, water vapour and volatile agents such as halothane.

METHOD

Adults of either sex undergoing general surgical, vascular or gynaecological procedures of $\frac{1}{2}$–$3\frac{1}{2}$ h duration were studied. All were premedicated with either an opiate and atropine or promethazine. Anaesthesia was induced with thiopentone and a muscle relaxant was given to allow insertion of a cuffed orotracheal tube. The relaxants were suxamethonium (spontaneous breathing) and alcuronium or pancuronium (IPPV).

Nitrous oxide and oxygen were supplied to the circuit. During spontaneous respiration halothane 1.5% was added from a Halox vaporizer; during IPPV halothane 0.5% was given. As far as possible, a similar depth of anaesthesia was provided at the lower flows, though the accuracy of the vaporizer is limited under such circumstances. Denitrogenation was performed using fresh gas flows of 6 litre/min for 10 min. In general, the passage of 24 litre provided time for stability of the inspired oxygen concentration after new settings of the flowmeters, representing at least three time constants for the volume of this system (Waters, 1968). Inspired oxygen % was recorded at 1-min intervals where possible.

J. A. RAYMOND, M.B., CH.B. (N.Z.), Timaru Hospital, Timaru, New Zealand.

The system used was a Boyle Mk III machine equipped with a 4-lb soda-lime absorber. Separate flowmeters were fitted for reduced flow rates (at 2 and 1 litre/min) and these were calibrated by the bubble burette method (Smith, 1970). Bulb samples were led from the inspiratory limb of the circle (figs. 1, 4, 7, 8) through a silica-gel column to a Servomex OA 150 analyser. Calibration was performed with 100% nitrous oxide, 100% oxygen and with room air. Errors from adsorption and elution of nitrous oxide from the silica gel were accepted in preference to the difficulty of dealing with samples of varying humidity. At flows below 6 litre/min all samples were returned to the

circuit at the inspiratory limb, but close to the Y-piece. This caused difficulty because of pressure being transmitted to the measuring cell, and occlusion of the sample tubing was often required during readings. The arrangement permitted repeated sampling of the fresh gas, with multiple changes of the oxygen percentage delivered during prolonged cases.

Study A. One hundred and thirty-seven patients were studied. If respiration was spontaneous the overflow was at the Y-piece (fig. 1). When IPPV was applied using a Bennett ventilator at the site normally occupied by the reservoir bag, the overflow was end-expiratory at the ventilator bellows (fig. 4).
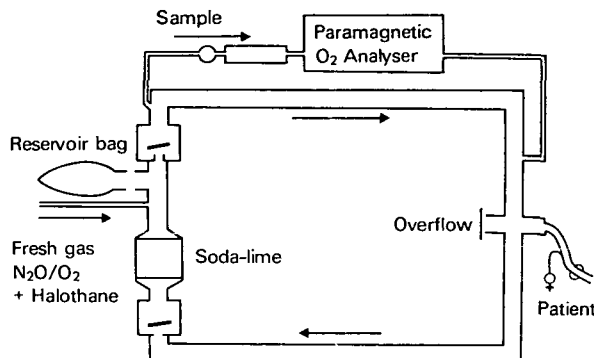

FIG. 1. Circuit for spontaneous respiration in Study A. Overflow valve at Y-piece. Samples taken from fresh gas flow and inspiratory limb at site shown. Fresh gas flows: 6, 3, 2 and 1 litre/min.
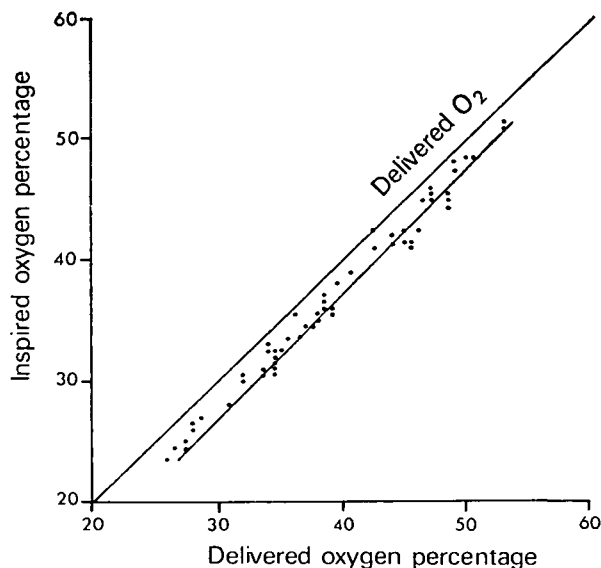

FIG. 2. Study A. Linear regression of inspired oxygen concentration % on delivered oxygen concentration %. Spontaneous respiration. Fresh gas flow: 2 litre/min. (Circuit of fig. 1.)
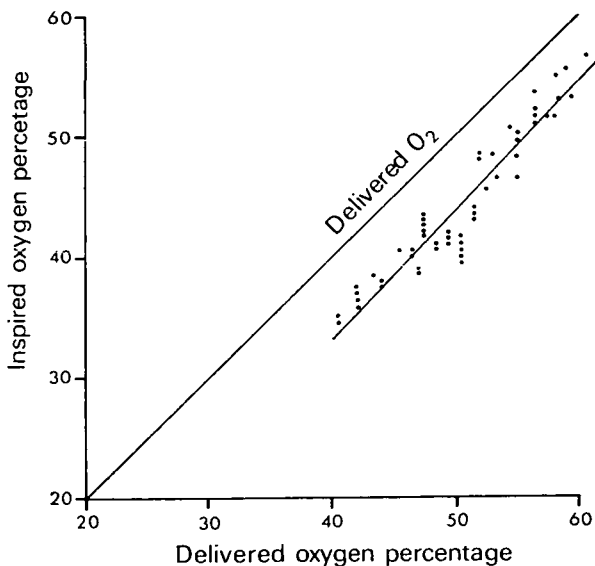

FIG. 3. Study A. Linear regression of inspired oxygen concentration % on delivered oxygen concentration %. Spontaneous respiration. Fresh gas flow: 1 litre/min. (Circuit of fig. 1.)
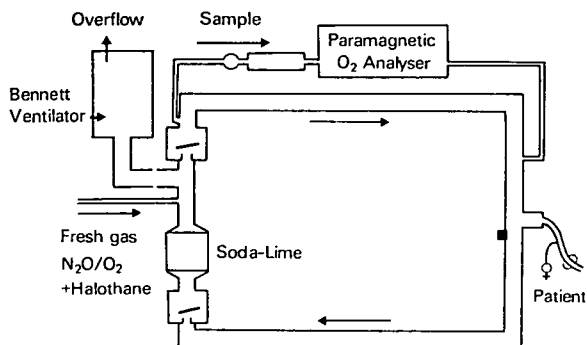

FIG. 4. Circuit for IPPV in study A. Overflow at ventilator in late expiration. Samples from fresh gas flow and from the inspiratory limb at site shown. Fresh gas flows of 6, 3, 2 and 1 litre/min.
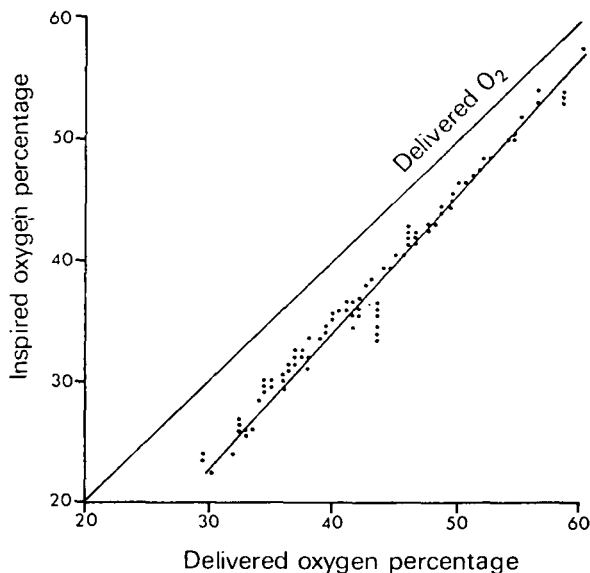
FIG. 5. Study A. Linear regression of inspired oxygen concentration % on delivered oxygen concentration %. IPPV. Fresh gas flow 2 litre/min. (Circuit of fig. 4.)
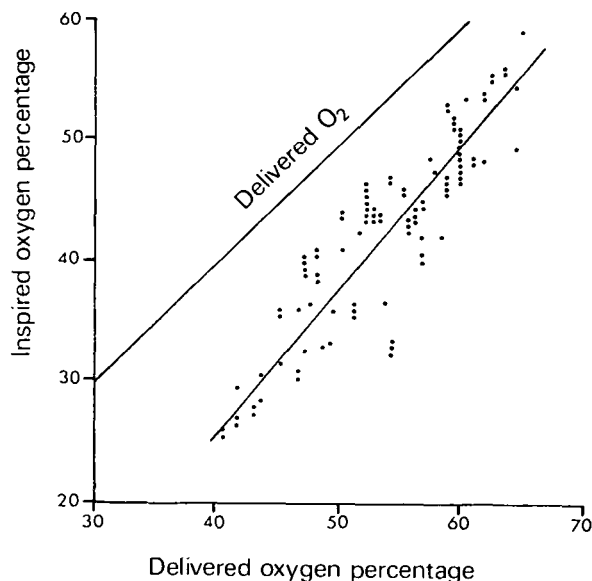

FIG. 6. Study A. Linear regression of inspired oxygen concentration % on delivered oxygen concentration %. IPPV. Fresh gas flow 1 litre/min. (Circuit of fig. 4.)

Study B. Twelve patients were studied with alternative arrangements of the same apparatus which were less favourable for the conservation of oxygen in the system during spontaneous respiration with the overflow at the inspiratory limb (fig. 7) and more

favourable during IPPV. To achieve overflow at the expiratory limb, an Ada valve replaced the usual Y-piece and the Bennett ventilator was attached to the expiratory limb (fig. 8). The Ada valve is an automatic non-rebreathing valve for either spontaneous or controlled respiration (Longworth Scientific Instruments Ltd). It has no overflow valve, and overflow was end-expiratory at the ventilator as before. This rather unusual arrangement was the only method of transferring the ventilator to the expiratory limb without extensive modification. The disc of the normal expiratory unidirectional valve was removed. Some resemblance may be seen to System F (Eger and Ethans, 1968).
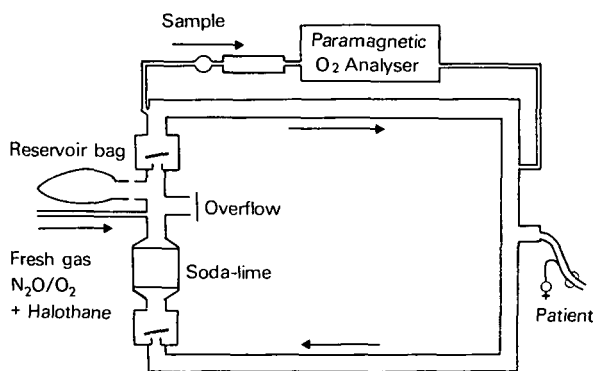

FIG. 7. Alternative circuit used in Study B for spontaneous respiration. The overflow valve was immediately distal to the site of fresh gas entry. Sampling from the fresh gas flow and from the inspiratory limb at the site shown. Fresh gas flow 2 litre/min.
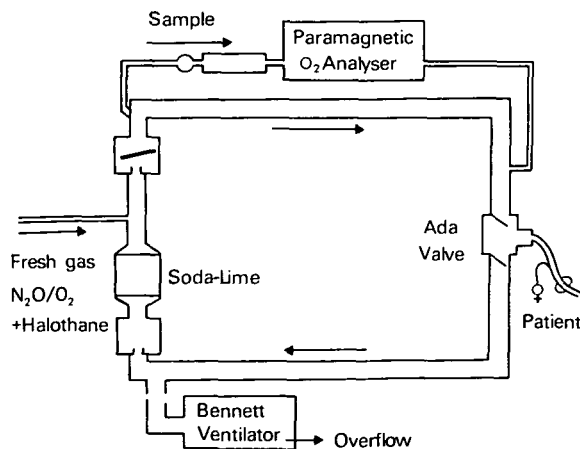

FIG. 8. Alternative circuit used in Study B for IPPV applied at expiratory limb, where overflow occurred. Ada valve shown. The disc of the expiratory unidirectional valve was removed. Samples from fresh gas flow and from inspiratory limb as shown. Fresh gas flow 2 litre/min.

RESULTS

Study A. The inspired oxygen % tended to attain a stable value at each of the fresh gas flows and conditions tested. After 10 min of denitrogenation, the time required for stability depended on the time taken for approximately 24 litre of fresh gas to flow into the circuit. This ranged from 4 min (6 litre/min) to 24 min (1 litre/min). The early stability of inspired oxygen % seemed surprising in view of the rapid changes in nitrous oxide uptake known to occur during the first hour of anaesthesia (Severinghaus, 1954; Barton and Nunn, 1975).

The inspired oxygen % remained relatively stable over periods of up to $3\frac{1}{2}$ h. Because of the changes in the delivered oxygen percentage, it was not possible to define precisely the effect of a prolonged period of time. However, the difference between delivered and inspired oxygen % frequently remained unchanged.

The difference increased as fresh gas flow was decreased. The scatter of readings increased also. The difference was always greater for IPPV, at a given fresh gas flow rate, than for spontaneous respiration. The scatter of readings was greater also. The difference was small at a fresh gas flow of 6 litre/min. Although it was greater at 3 litre/min and greater still at 2 litre/min, the scatter was not significant clinically.

The effect of reducing the fresh gas flow was greater as the delivered oxygen percentage was decreased. This effect was more marked during IPPV than during spontaneous respiration.

Linear regressions of inspired oxygen % on delivered oxygen % were performed under the eight conditions of Study A (table I). In all cases the linear relationship was statistically significant ($P < 0.01$).

TABLE I. *Study A: Linear regressions of inspired oxygen % on delivered oxygen % using nitrous oxide, oxygen and halothane admitted to a circle system. The circuit is shown in figure 1 for spontaneous respiration and figure 4 for IPPV*

Fresh gas flow (litre/min)	Respiration	Regression equation* x	y	Correlation coefficient (r)
6	Spontaneous	0.988	0.253	0.998
6	IPPV	0.960	0.659	0.993
3	Spontaneous	1.014	−1.059	0.994
3	IPPV	1.019	−2.811	0.994
2	Spontaneous	1.054	−4.782	0.954
2	IPPV	1.136	−11.150	0.994
1	Spontaneous	1.089	−10.063	0.978
1	IPPV	1.200	−21.886	0.912

* Inspired concentration $= x \times$ delivered concentration $+ y$.

The eight lines were significantly different ($P < 0.01$) and had significantly different slopes ($P < 0.01$).

The two lines at each of the four flow rates were compared and the slopes were significantly different at 6 and 2 litre/min, but not at 3 and 1 litre/min of fresh gas flow. The eight lines of table I were tested further to see if there was any evidence of curvature. There was a significant parabolic trend in two lines (6 litre/min IPPV and 3 litre/min spontaneous) ($P < 0.01$), but in none of the other six lines. At 6 litre/min IPPV the equation was:

$$\text{Inspired oxygen \%} = 1.504 \, O_d\% - 0.00749 \, O_d\%^2 - 9.029$$

and at 3 litre/min spontaneous respiration:

$$\text{Inspired oxygen \%} = 0.699 \, O_d\% + 0.00422 \, O_d\%^2 + 4.708.$$

($O_d\%$ = delivered oxygen %).

Neither of these equations demonstrates any tendency to a steep reduction in inspired oxygen % when delivered oxygen % is in the range 20–30%.

The data obtained at 1 litre/min of fresh gas flow with IPPV were examined. When the average discrepancy between delivered oxygen and inspired oxygen % was calculated for each of these 25 patients, it was seen to be greater in males than in females. The scatter of values for inspired oxygen % was considerable and an analysis was made of any relationship of the discrepancy to physical factors in the patients studied. The possible linear relationships between the difference of delivered and inspired oxygen % and age, height, weight, calculated surface area, calculated rate of oxygen uptake per square metre and calculated total oxygen uptake were investigated (Geigy Scientific Tables, 1962).

The relationship to height was found to be significant for females only. The results for age and the calculated rate of oxygen uptake (ml m⁻² min⁻¹) were not significant.

TABLE II. *Study A: Linear regressions: difference between delivered and inspired oxygen % on four physical variables (height, weight, surface area and oxygen consumption). Fresh gas flow rate 1 litre/min with IPPV*

Females	Difference = 0.473 height (in) − 21.364
Males	Difference = 0.164 weight (kg) + 2.489
Females	Difference = 0.164 weight (kg) − 1.129
Males	Difference = 9.278 surface area (m²) − 2.860
Females	Difference = 9.278 surface area (m²) − 6.590
Males	Difference = 0.057 O_2 uptake (ml/min) + 0.927
Females	Difference = 0.057 O_2 uptake (ml/min) − 2.555

Statistically significant relationships are shown in table II: difference v. height (for females), weight (males and females), calculated surface area in square metres (males and females), and calculated oxygen uptake in ml/min.

Hence for the whole group body weight proved to be an important variable, but, in females, height was the more important factor.

Study B. With the circuit shown in figure 7 and with fresh gas flows of 2 litre/min with spontaneous respiration, a significantly different regression line was obtained from the previous experiment ($P < 0.01$):

$$\text{Inspired oxygen } \% = 0.947 \text{ O}_d\% - 1.699.$$

At most settings the inspired oxygen % was lower than that for the circuit in figure 1.

With the circuit in figure 8 and with fresh gas flows of 2 litre/min with IPPV a significantly different regression line was obtained from the previous experiment ($P < 0.01$):

$$\text{Inspired oxygen } \% = 1.068 \text{ O}_d\% - 6.504.$$

At all settings the inspired oxygen % was higher than with the circuit in figure 4.

DISCUSSION

If nitrous oxide and oxygen are delivered to a circle system, a decrease in the oxygen percentage of any sample derived from the system must depend upon the content of alveolar gas in that sample. More alveolar gas will be present in the expiratory than in the inspiratory limb. For spontaneous respiration the overflow at the Y-piece allows a selective loss of alveolar gas. For IPPV an overflow at the expiratory limb is more favourable. It seems likely that if the site and timing of overflow were comparable, the results would be similar for spontaneous respiration and IPPV.

Many anaesthetic circuits are poorly designed for the optimum overflow of alveolar gas as compared with fresh gas, the overflow being sited on the inspiratory limb, even immediately distal to the site of fresh gas inflow (fig. 7).

Crowley, Faulconer and Lundy (1948) studied various inflows to a circle system using nitrogen in oxygen mixtures. Foldes, Ceravolo and Carpenter (1952) used a simple formula taking into consideration the nature and amount of fresh gas flow and the oxygen uptake. However, continued nitrous oxide uptake and variable losses from the overflow valve were ignored. The predictions suggested that the inspired oxygen % would decrease in response to a

reduction in fresh gas flow, a reduction of oxygen % in that flow, and as a result of prolonged anaesthesia. This latter proposition has not been supported by the present study.

Smith (1966) studied expiratory limb losses from a circle system at fresh gas flows less than 1200 ml/min. He attempted to improve on Foldes' formula by adding the equation of Severinghaus (1954) for nitrous oxide uptake, with corrections for the nitrous oxide concentration inspired and for body weight. No accurate prediction proved possible from either equation and no improvement was obtained by consideration of weight, age, sex or operation site.

However, Forbes (1972) applied the formulae of Foldes and of Mushin and Galloon (1960) and that of the theoretical analysis of Fitton (1958, 1963) to subjects breathing spontaneously, the overflow valve being placed at the Y-piece. Acceptable predictions were claimed.

Comparison of much of the literature is difficult because a variety of circuit designs has been used, and in many cases the layout is not described. Sampling sites vary: these may be at the inspiratory or expiratory limb or even at the Y-piece (Sara, 1961).

The only reports which considered the effect of circuit design on inspired oxygen % were those of Schillig and Weis (1973) and Oeking and Weis (1973). However, the inspired oxygen was expressed as a percentage of delivered oxygen. This would be valid only if the discrepancy between the two diminished as the proportion of oxygen in the fresh gas decreased.

In the present study no attempt has been made to derive an equation for gases entering and leaving the system. Instead, the decrease and variation of inspired oxygen %, occurring in any situation in which the alveolar gas of the sample is increased, has been related to fresh gas flow rate, circuit design and to the physical factors in the patients studied.

With spontaneous respiration the siting of the overflow valve at the Y-piece has unique advantages for the elimination of alveolar gas. Variation of inspired oxygen % about the regression line at 1 litre/min was $\pm 3\%$ (fig. 3). With IPPV mixing of alveolar gas is difficult to avoid, wherever the overflow is sited. With IPPV by a ventilator (and overflow) sited at the inspiratory limb and a fresh gas flow of 1 litre/min the variation of inspired oxygen % about the regression line was $\pm 6\%$ (fig. 6). For the latter circumstances the average delivered–inspired oxygen difference was tabulated for each patient. Using the equation for weight as a predictor, the average error for men, in six cases, was 1.3%. Using the equation

for height as a predictor in 17 females, the average error was only 0.9% of oxygen.

Studies were performed also on the oxygen concentration of gas found in the expiratory limb of several circuits. There was a greater reduction in these samples than in the corresponding inspiratory limb, with greater variability. In any situation where sampled oxygen was reduced below the delivered value, variability occurred—this was *between* rather than *within* patients. The relevance of patient height and weight and of calculations derived from these suggests that variations in the nature of alveolar gas, depending on the extent of its presence, caused this phenomenon.

Any consideration of a low inflow circle system must assume a carefully monitored fresh gas flow, but the lack of accuracy of rotameters for lower settings discourages the use of such a technique. Greater accuracy in standard equipment would encourage the use of nitrous oxide and oxygen at 2 litre/min fresh gas flows, when a setting of 1200 and 800 ml/min would ensure an inspired oxygen concentration above 30%.

At 1 litre/min of fresh gas flow, the inspired oxygen may be 20% less than the percentage delivered. The use of nitrous oxide and oxygen at 500 and 500 ml/min as Entonox would again ensure an inspired oxygen concentration above 30%.

Denitrogenation and a period of high flow rate are necessary after any disconnection. The period will depend upon the volume of the circle system.

REFERENCES

Barton, F., and Nunn, J. F. (1975). Totally closed circuit nitrous oxide/oxygen anaesthesia. *Br. J. Anaesth.*, 47, 350.

Crowley, J. H., Faulconer, A., and Lundy, J. S. (1948). Certain factors influencing the percentage of oxygen in mixtures of nitrous oxide and oxygen. *Anesth. Analg. (Cleve.)*, 27, 255.

Eger, E. I., and Ethans, C. T. (1968). The effects of inflow, overflow and valve placement on economy of the circle system. *Anesthesiology*, 29, 93.

Fitton, E. P. (1958). A theoretical investigation of oxygen concentrations in gases inspired from various semi-closed anaesthetic systems. *Br. J. Anaesth.*, 30, 269.

—— (1963). Theoretical investigation of oxygen concentrations: correction and additional observations (correspondence). *Br. J. Anaesth.*, 35, 276.

Foldes, F. F., Ceravolo, A. J., and Carpenter, S. L. (1952). The administration of nitrous oxide–oxygen anesthesia in closed systems. *Ann. Surg.*, 136, 978.

Forbes, A. R. (1972). Inspired oxygen concentrations in semi-closed circle absorber circuits with low flows of nitrous oxide and oxygen. *Br. J. Anaesth.*, 44, 1081.

Geigy Scientific Tables (1962). 6th edn.

Mushin, W. W., and Galloon, S. (1960). The concentration of anaesthetics in closed circuits with special reference to halothane. *Br. J. Anaesth.*, 32, 324.

Oeking, G., and Weis, K. H. (1973). On the oxygen concentration in the anaesthetic circle system. II: Dependence on the type of circle system. *Anaesthesist*, 22, 202.

Sara, C. (1961). The oxygen content of anaesthetic mixtures. *Med. J. Aust.*, 2, 81.

Schillig, R., and Weis, K. H. (1973). On the oxygen concentration in the anaesthetic circle system. I: Dependence on fresh gas flow. *Anaesthesist*, 22, 198.

Severinghaus, J. W. (1954). The rate of uptake of nitrous oxide in man. *J. Clin. Invest.*, 33, 1183.

Smith, T. C. (1966). Nitrous oxide and low inflow circle systems. *Anesthesiology*, 27, 266.

—— (1970). Calibration of gas flowmeters with the bubble burette. *Anesthesiology*, 33, 553.

Waters, D. J. (1968). Factors causing awareness during surgery. *Anaesthesia*, 40, 259.

PREDICTION DE LA CONCENTRATION D'OXYGENE INSPIRE DANS UN SYSTEME D'ANESTHESIE EN CIRCUIT FERME

RESUME

Des débits de gaz frais, de protoxyde d'azote, d'oxygène et d'halothane à raison de 6, 3, 2 et 1 litre/min ont été introduits dans un système d'absorption en circuit fermé. On a étudié la respiration spontanée et l'IPPV (ventilation au moyen de respirateurs à pression positive intermittente) et on a calculé le pourcentage de la concentration d'oxygène délivré par rapport à la régression de l'oxygène inspiré. La différence entre le pourcentage de concentration de l'oxygène inspiré et l'oxygène délivré a été augmentée en diminuant le débit de gaz frais et en diminuant la proportion d'oxygène dans ce débit, particulièrement pendant l'IPPV. Les circuits conçus pour permettre un débordement maximal de gaz alvéolaire ont donné une plus grande concentration d'oxygène inspiré. La taille et le poids du patient ont été reliés à la dispersion des valeurs observées de gaz inspiré à 1 litre/min de débit de gaz frais pendant l'IPPV.

VORHERSAGE UND BESTIMMUNG DER EINGEATMETEN SAUERSTOFFKONZEN- TRATION INNERHALB EINES KREISNARKOSESYSTEMS

ZUSAMMENFASSUNG

Gaszirkulation von frischem Stockstoff, Sauerstoff und Halothan in Dosierungen von 6, 3, 2 und 1 Liter/Min wurde in ein Kreisnarkosesystem eingeführt. Die Spontanatmung und IPPV wurden beobachtet und der Atmungspachlass nach konzentrierter Sauerstoffzuführung wurde prozentuell ermessen. Der prozentuelle Unterschied

zwischen der zugeführten und der eingeatmeten Sauerstoff-konzentration wurde vergrössert, in dem man die Zufuhr frischer Gases erniedrigte, sowie auch mittels proportioneller Herabseztung des Sauerstoffs, innerhalb dieses Kreises, besonders während IPPV. Da die Konstruktion des Leitungsapparats maximalen Sicherheitsabfluss der alveolaren Gase ermöglichte, ergab sich eine erhöhte Einatmungskonzentration von Sauerstoff. Körpergewicht, sowie Grösse der Patienten wurden auf die (statistische) verbreitung der Einatmungswerte bei 1 Liter/Min frischer Gaszirkulation mit IPPV bezogen.

PREDICCION DE LA CONCENTRACION DE OXIGENO INSPIRADO DENTRO DE UN SISTEMA ANESTESICO DE CIRCULO

SUMARIO

Se introdujeron flujos de gas fresco de óxido nitroso, oxígeno y halotano a 6, 3, 2 y 1 litros por minuto en un sistema absorbente de círculo. Se estudiaron la respiración espontánea y el IPPV y se calculó una regresión de la concentración inspirada sobre la concentración transmitida (por ciento) del oxígeno. La diferencia entre las concentraciones transmitida y inspirada del oxígeno se incrementó mediante la disminución del flujo de gas fresco y la disminución de la proporción de oxígeno en ese flujo especialmente durante el IPPV. Los circuitos diseñados para permitir un máximo de escape de flujo de gas alveolar proporcionaron una concentración mayor de oxígeno inspirado. La altura y el peso de los pacientes fueron relacionadas con la dispersión de los valores inspirados observados en un litro por minuto de flujo de gas fresco durante el IPPV.