# FUNCTIONAL RESIDUAL CAPACITY (FRC) AND COMPLIANCE IN ANAESTHETIZED PARALYSED CHILDREN

## Part I: *in vitro* Tests with the Helium Dilution Method of Measuring FRC

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### INTRODUCTION

IN ADULTS, anaesthesia and intermittent positive pressure ventilation (IPPV) lead to a reduction in functional residual capacity (FRC). Relatively more of the inspired gas is distributed to the uppermost lung areas instead of to the dependent zones which receive more of the pulmonary blood flow.[1] However, the magnitude of this fall in FRC is not great.[2,3]

The effect of anaesthesia and IPPV upon FRC in children is not known, although severe falls in FRC have been noted following cardiac surgery in infants.[4] Differences in body configuration and lung structure may result in greater or lesser changes than those observed in adults.

This paper describes a technique for measuring FRC by the helium dilution method during surgery in children, and reports on the accuracy of the method when tested in the laboratory.

### METHODS

To use the helium dilution method of measuring FRC during anaesthesia, we overcame three major difficulties. We designed a ventilator which would permit a patient at FRC to be switched in and out of a helium closed circuit without causing any change in the pattern of ventilation. During the period of measurement we added oxygen to the circuit in sufficient quantities to prevent changes in the circuit volume measured by spirometer and kymograph. We calibrated the helium catharometer for the effect of various concentrations of oxygen and nitrogen, nitrous oxide and methoxyflurane.

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This work was supported by a grant from The Physicians' Services Incorporated Foundation and grant number MA-3761 from The Medical Research Council of Canada. Some of the apparatus used in this investigation was purchased with the aid of a grant from the Canadian Red Cross Youth (Ontario).

Paper read by T.L. Dobbinson at the Royal Australasian College of Surgeons 45th General Scientific Meeting, Hobart, Tasmania, 1972.

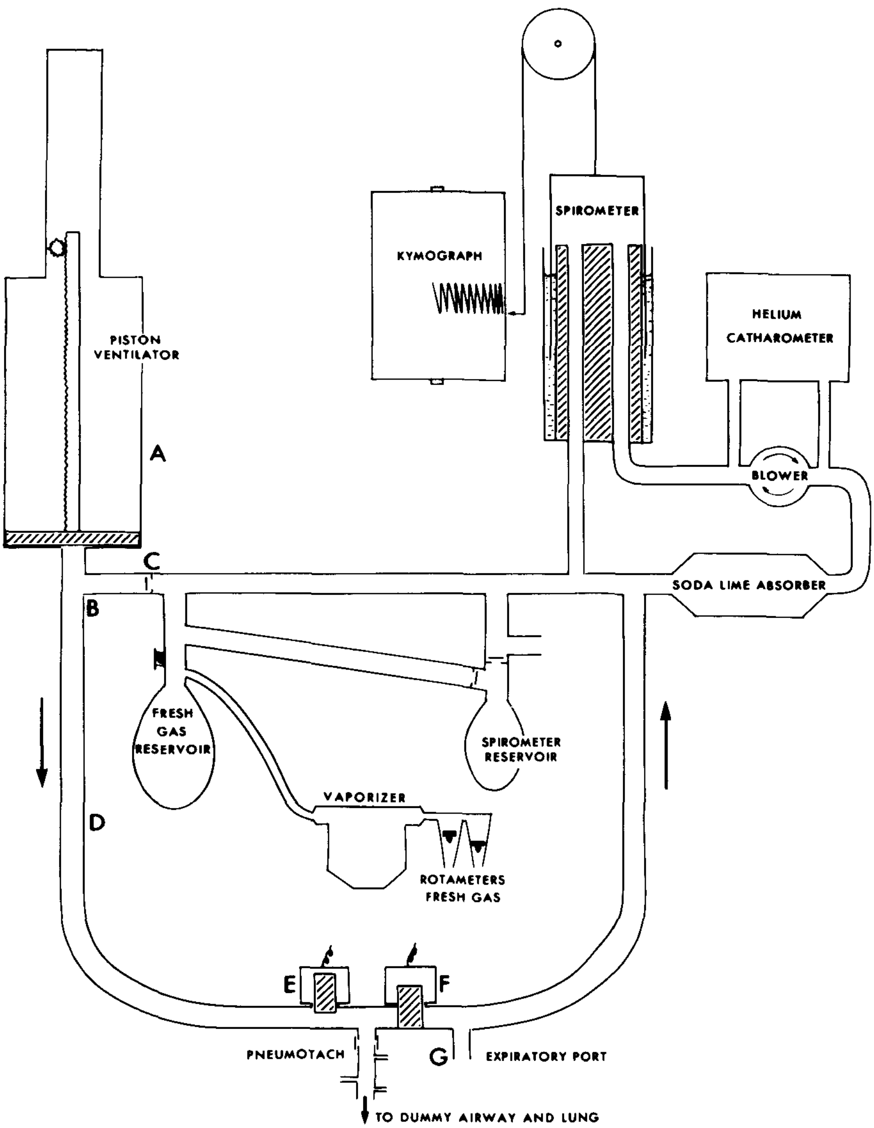


FIGURE 1. Piston ventilator and FRC measuring circuit.

*Design of the ventilator and recording circuit*

A simple piston-type ventilator was designed as shown in Figure 1. An air-tight cylinder (A) was added to a calibrated 1500-ml Hamilton syringe so that the piston of the syringe could be moved in and out by applying alternating positive and negative pressure phases to the cylinder. An electronic circuit was constructed to allow the pattern of ventilation to be varied and controlled.[5,6]

Through one limb of an attached T-piece (B) the syringe could fill through a one-way valve (C) with a mixture of gases supplied to a reservoir bag from

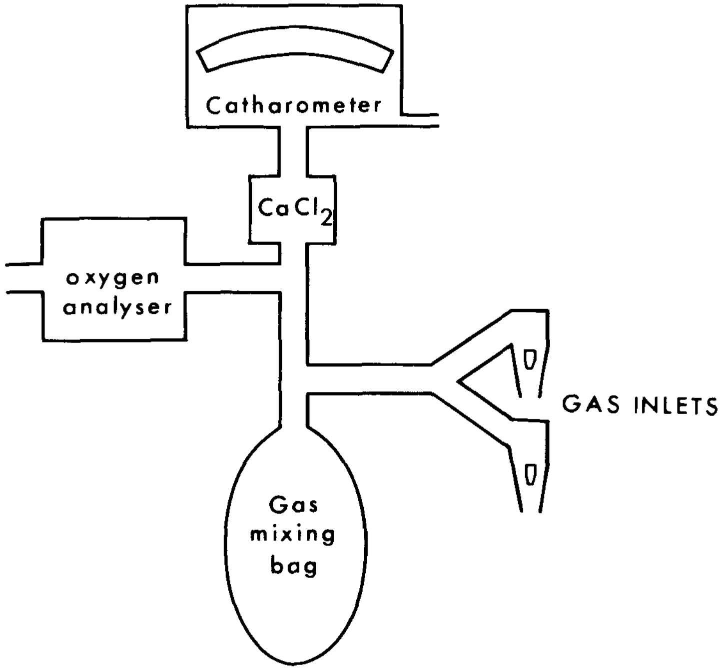


FIGURE 2. Circuit for catharometer calibration tests.

standard anaesthetic rotameters and a vapourizer.* When the syringe emptied, it expelled these gases through non-distensible Teflon tubing (D) and a solenoid valve (E) into a dummy lung constructed from a 1500-ml Hamilton super-syringe and a strong spring to simulate low compliance. On expiration, the gases passed through another solenoid valve (F) and could then be collected at (G) in a bag, or directed to the atmosphere; or caused to enter a closed circuit containing soda lime to absorb carbon dioxide, a helium catharometer† (full scale, 0–15 per cent helium) and a spirometer (1 liter, with blocked internal dead space) attached to a kymograph. The circuit also included a blower motor‡ to permit gas mixing and a chamber containing silica gel to remove water vapour before it reached the helium catharometer.

This ventilator permits quick switching from a non-breathing open circuit to a closed circuit containing helium without disturbing the pattern of ventilation. By stopping the ventilator in expiration, clamping the inspiratory and expiratory limbs and releasing the clamps separating the helium circuit, we would be able to introduce a patient into the closed circuit in less than 10 seconds and commence measuring FRC. Once introduced into the closed circuit the patient would be provided with metabolic oxygen through a needle valve.

*Effect of different gas mixtures and volatile agents upon the helium catharometer*

The performance of the helium catharometer is affected by such agents as nitrous oxide, halothane[7] and methoxyflurane; in addition, its response varies with the

*Pentec, Cyprane Ltd., Keighley, England.
†Warren Collins, Braintree, Massachusetts, U.S.A.
‡Warren Collins, Braintree, Massachusetts, U.S.A.

proportions of nitrogen and oxygen in the inspired gas mixture. To quantify these effects we passed various gas mixtures through the catharometer and noted the deflections produced on the scale.

*Oxygen-nitrogen mixtures*: Various oxygen-nitrogen mixtures were prepared by mixing air and oxygen in a Y-piece leading into a rubber bag (Figure 2). From this bag the mixture could be squeezed through the catharometer, and by a T-piece through an oxygen analyzer.* When both instruments had been flushed, readings were made at atmospheric pressure. Seventy such measurements were made on 11 different mixtures of gas containing approximately 20 to 100 per cent of oxygen in nitrogen. We plotted the oxygen concentrations against the changes from zero produced in the catharometer readings.

*Methoxyflurane-air mixtures*: Mixtures of methoxyflurane and air in various concentrations were prepared by passing air through a calibrated vapourizer.† Since methoxyflurane produces a negative deflection in the reading of the catharometer, the zero position of the needle was readjusted to 1 per cent. Before the mixture entered the catharometer it was sampled by means of a glass syringe and analyzed in a gas analyzer.‡ The various concentrations of methoxyflurane in air were plotted against the negative deflections obtained.

Since silica gel is sometimes used to absorb methoxyflurane,[8] we tested its efficiency in removing this vapour from the circuit by replacing the calcium chloride in the water-vapour absorption chamber of the catharometer with silica gel and repeating the measurements.

*Nitrous oxide-air mixtures*: Various proportions of nitrous oxide and oxygen were mixed and passed through the catharometer and the effects were noted.

*Measurement of a Known Volume in the Dummy Lung*

*Preparing the circuit*: The helium meter was switched on at least 30 minutes before use and the circuit was tested for leaks with the mixing motor at full speed, by placing weights on the spirometer bell. We then adjusted the motor speed to the operational level and balanced the circuit by placing sufficient weight on the spirometer bell to produce atmospheric pressure at the expiratory port (G, Figure 1).

The helium measuring circuit was flushed with air and the catharometer needle was adjusted to the zero position. This procedure was repeated until stable values were obtained.

We next flushed the combined circuits and the dummy lung with a gas mixture containing known concentrations of oxygen, nitrogen and methoxyflurane, then switched the blower motor off and drew a quantity of the gas into the spirometer bell at atmospheric pressure. After closing off the spirometer circuit with a clamp, we recorded the deflection of the catharometer needle from the zero position. This value was later used to correct the helium reading for the effect of the combined gas mixture.

Next we introduced 200 ml of helium at atmospheric pressure into the spiro-

*Servomex Controls Ltd., Crowborough, Sussex, England.
†Pentec, Cyprane Ltd., Keighley, England.
‡Ohio Medical Products, A Division of Air Reduction Company Inc., Madison, Wisconsin, U.S.A.

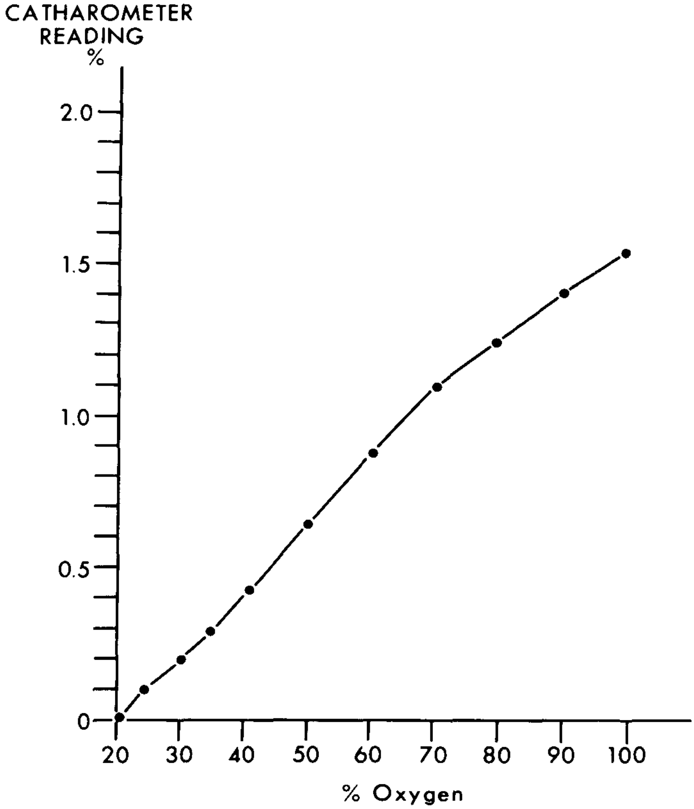


FIGURE 3. Catharometer calibration curve for effect of varying concentrations of oxygen in nitrogen.

meter and thoroughly mixed the gases in the circuit. The initial helium concentration was 12.5 per cent.

For reasons not understood we found it necessary to repeat the priming procedure three times, otherwise the catharometer gave a variable over-estimate of a known measured volume.

Once priming was complete and the spirometer and ambient temperatures were recorded, the ventilator was stopped at the end of an inspiratory stroke; fresh gas inflow and "expired gas" outflow were halted by means of clamps.

*Volume measurement*: The dummy lung was filled with 500, 1000 and 1500 ml of the gas mixture and ventilated on the closed circuit. Final helium concentration was read from the catharometer and final oxygen concentration was measured with a paramagnetic oxygen analyzer* when mixing was complete.

In the calculation of dummy lung volume, two methods were used to correct the helium concentrations for oxygen in the circuit. In the first method, we used the appropriate factor derived from the graph of the effects of different oxygen concentrations upon the catharometer (Figure 3) to correct both the initial and final

*Servomex Controls Ltd., Crowborough, Sussex, England.

helium readings. Direct measurement of initial oxygen concentration would require the removal of a sample of gas from the spirometer and thus would introduce errors during the clinical measurement of FRC. So we calculated the initial oxygen concentration from the volume of the closed circuit with the spirometer bell in the maximally depressed position (the "block volume"), the circuit volume after addition of a volume of gas with known oxygen concentration, and the circuit volume after the addition of a known volume of helium.

For example:

| | ml | |
|---|---|---|
| "Block volume" after flushing with $50\%\ O_2$ in $N_2$ | 1000 | 1400 ml (1000 + 400) |
| Added volume of $50\%\ O_2$ in $N_2$ | 400 | |
| Added volume of pure He | 200 | |
| Total circuit volume | 1600 | |

$$\text{Concentration of } O_2 \text{ in circuit} = \frac{0.5 \times 1400}{1600} = 7/16 = 40\%$$

The accuracy of this method of estimating initial oxygen concentration in the circuit was verified by direct measurement in several experiments. Calculated and measured values were within 2 per cent of each other.

In the second method the catharometer was set with air and the effect of the oxygen-nitrogen-methoxyflurane mixture upon the reading was observed. The change in the observed reading was then used to correct both the initial and final helium values.

The volume of tubing outside the priming circuit was determined, since this dead space adds to the dilution of helium, and dummy lung volumes at ATPS ($FRC_{ATPS}$) were calculated from the equation:

$$FRC_{ATPS} = \frac{45.6A\,[(He_{in} - O_{2in}) - (He_f - O_{2f})]}{(He_{in} - O_{2in})\,(He_f - O_{2f})} - V_D$$

where:
$A$ = height of helium in spirometer in cm
$He_{in}$ = initial observed helium concentration
$He_f$ = final observed helium concentration
$O_{2in}$ = initial oxygen correction factor
$O_{2f}$ = final oxygen correction factor
$V_D$ = dead space volume

The $FRC_{ATPS}$ values were then converted to the corresponding volumes at STPD.

## Results

*Effects of different gas mixtures and volatile agents upon the catharometer*

*Oxygen-nitrogen mixtures* (Figure 3): The relationship between catharometer readings and concentration of oxygen in nitrogen was reasonably linear.

*Methoxyflurane-air mixtures* (Figure 4): Greater concentrations of methoxy-

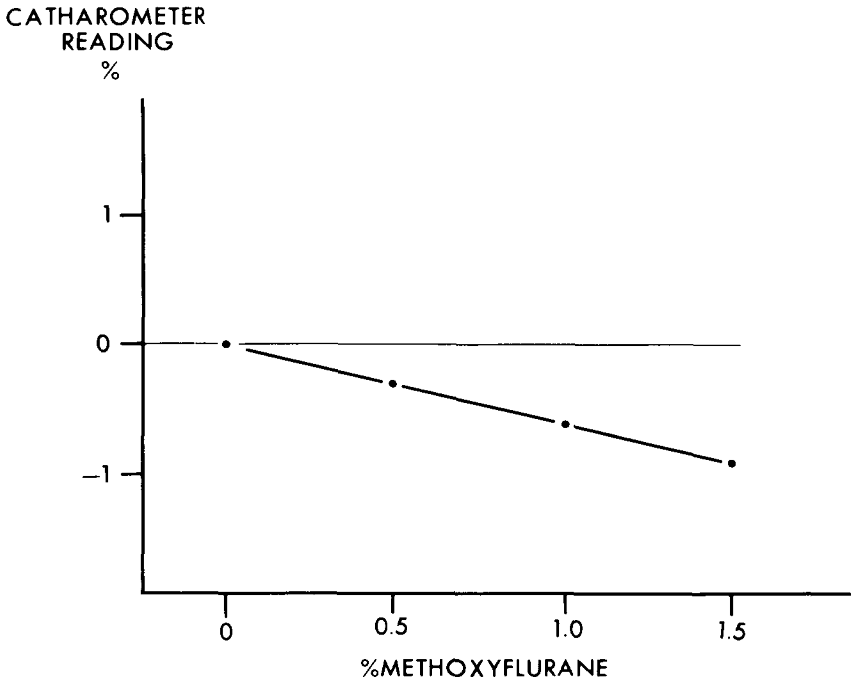


FIGURE 4. Effect of methoxyflurane on catharometer calibration.

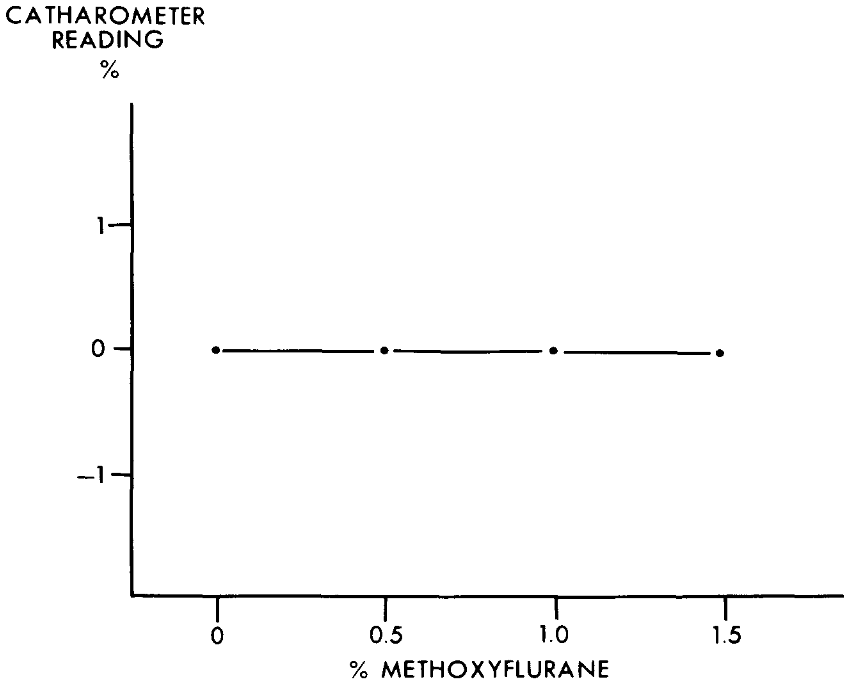


FIGURE 5. Effect of methoxyflurane on catharometer calibration after adsorption by silica gel

TABLE I

EFFECT OF NITROUS OXIDE ON HELIUM CATHAROMETER

| $\%N_2O$ | Negative Deflection |
|---|---|
| 1.2 | 0.06 |
| 2.4 | 0.20 |
| 3.6 | 0.42 |
| 4.8 | 0.60 |
| 6.0 | 0.80 |

flurane (0.5 to 1.5 per cent) produced greater negative deflections from zero. These negative deflections were entirely abolished when the methoxyflurane was absorbed by silica gel (Figure 5).

*Nitrous oxide-air mixtures* (Table I): Even with low concentrations of nitrous oxide the negative deflections of the catharometer needle were greater as the concentration increased.

*Measurement of dummy lung volume*

Figures 6 and 7 correlate known volume and measured volume for 1 per cent methoxyflurane in pure oxygen and in 50 per cent oxygen-nitrogen respectively.

When we corrected the measured volumes for different oxygen concentrations by either of the methods described we obtained good correlation between measured volumes and known volumes.

500-ml volumes were measured repeatedly with a coefficient of variation of $<4.7$; 1000-ml with a coefficient of variation of $<2.6$; and 1500-ml with a coefficient of variation of $<1.25$.

## DISCUSSION

Since the dummy lung and the tubing external to the spirometer closed circuit contained 50 per cent oxygen in nitrogen before volume measurement commenced, in some of these experiments mixing of the gas in the spirometer and gas in the dummy lung produced a small increase (3 per cent) in the nitrogen concentration in the helium catharometer. This did not affect the accuracy of the volume measurement.

Other errors which must be considered when the technique is introduced into clinical practice include the absorption of helium by the patient, changes in the respiratory exchange ratio (R) and "switch in" error.

Meneely *et al.*,[9] measuring FRC in adults, calculated that absorption of helium results in an over-estimate of 100 ml, nitrogen increment in an over-estimate of 75 ml, and that the correlation for R is insignificant (30 ml). Taken together, these factors result in an over-estimate of 200 ml (about 6 per cent). Because of scepticism regarding the application of any of these correction factors at many respiratory function laboratories, including that at The Hospital for Sick Children, Toronto, we do not intend to use them in clinical measurements under anaesthesia.

In contrast, it is easy to correct for "switch-in" error. When the patient is switched into the circuit, a small volume of gas may be transferred to or from the

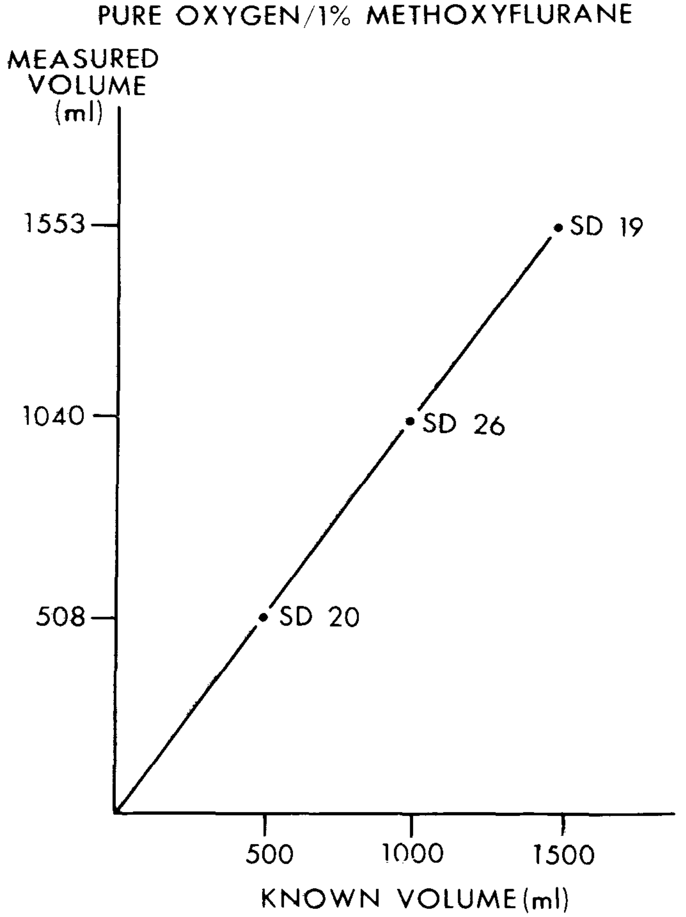


FIGURE 6. Correlation between measured and known dummy lung volumes with pure oxygen and 1 per cent methoxyflurane.

spirometer. During artificial ventilation, if the circuit is balanced to atmospheric pressure at the mouth, the transfer can only be in the direction of the spirometer. The volume transferred ("switch-in volume") is shown on the kymograph (D-E, Figure 8) and is subtracted from the value measured for FRC.

Such errors are rarely encountered in clinical practice if the paralysed patient is switched into the circuit after a complete expiration. The closed-circuit volume is small in relation to the inspiratory capacity of large children and in such cases it is wise to maintain adequate neuro-muscular block to prevent aspiration of water from the spirometer into the inspiratory tubing.

## SUMMARY

This paper is the first part of a report on a method of measuring FRC by the helium dilution method in anaesthetized children during artificial ventilation. It describes laboratory investigations of the effects of different concentrations of

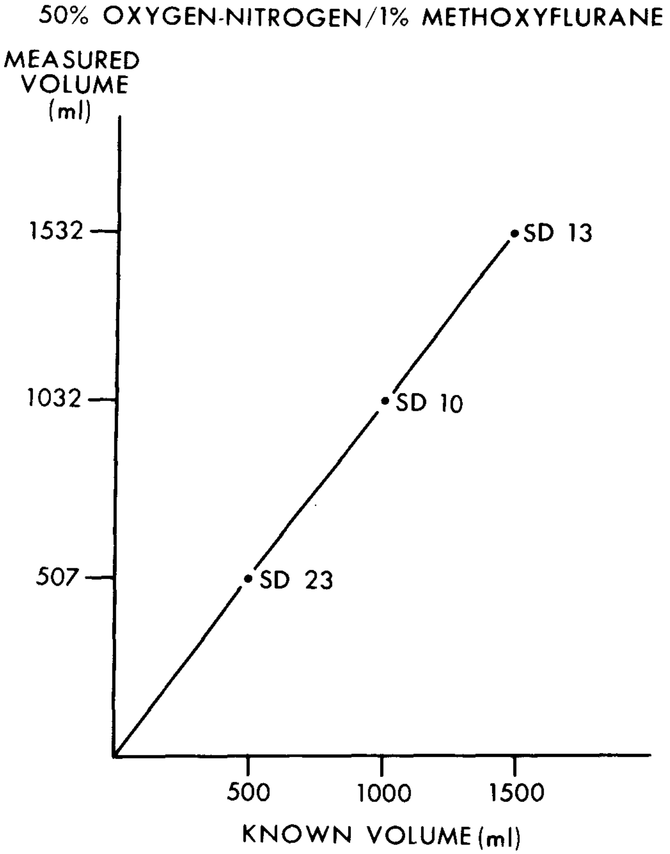


FIGURE 7. Correlation between measured and known dummy lung volumes with 50 per cent oxygen in nitrogen and 1 per cent methoxyflurane.

oxygen, nitrogen and methoxyflurane upon the accuracy with which known volumes can be determined in a "dummy lung." For a volume of 500 ml the coefficient of variation was <4.7; for 1500 ml it was <1.25. Results of using the technique to measure changes in FRC in anaesthetized paralysed children are to be reported in Part II.

## Résumé

Cet article est la première partie d'un rapport sur la méthode de mesurer la C.R.F. par la dilution d'hélium chez les enfants anesthésiés et ventilés artificiellement. Nous décrivons les recherches de laboratoire sur les effets de différentes concentrations d'oxygène, d'azote et de méthoxyflurane sur la précision avec laquelle des volumes connus peuvent être déterminés dans un poumon robot. Pour un volume de 500 ml le coefficient de variation était <4.7; pour 1500 ml, il était <1.25. Les résultats de l'usage de la technique pour mesurer les changements de la C.R.F. chez des enfants anesthésiés et paralysés paraîtront dans la deuxième partie.

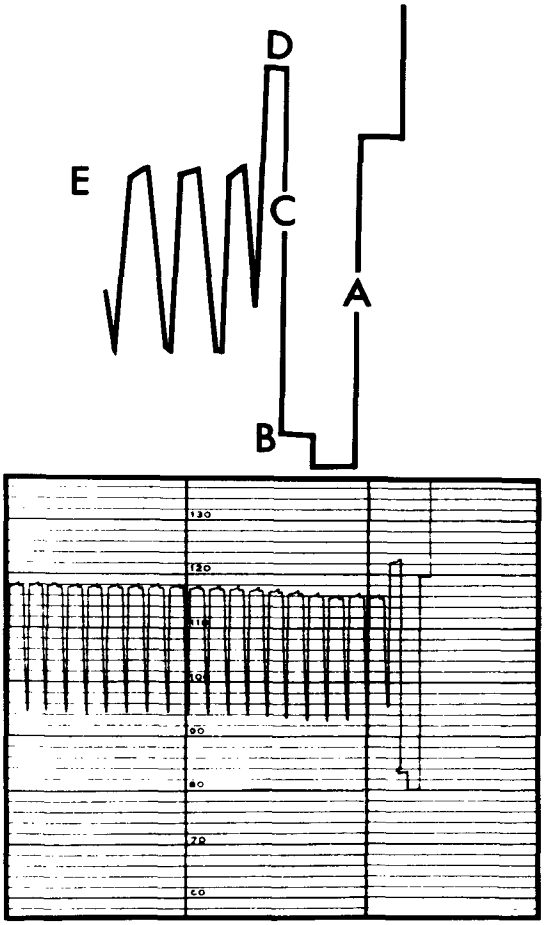


FIGURE 8. Kymograph record showing switch-in error.
A – helium and gas mixture added to closed circuit.
B – weights placed on bell with blower motor on.
C – tidal volume drawn into piston ventilator.
D – switch-in point.
E – resting circuit volume after switch-in.
(D–E) ml is the switch-in error ATPS.

ACKNOWLEDGMENT

We wish to thank the Departments of Medical Publications and Visual Education, The Hospital for Sick Children, Toronto, for their help in preparing this paper for publication.

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