THE MEASUREMENT OF OXYGEN UPTAKE IN INFANTS WITH
CONGENITAL HEART DISEASE DURING GENERAL ANAESTHESIA
AND INTERMITTENT POSITIVE PRESSURE VENTILATION

BY

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SUMMARY

Measurements of oxygen uptake ($V_{O_2}$) were carried out in infants with congenital heart
disease using a circuit devised for use during the nitrous oxide/oxygen, controlled
ventilation sequence of general anaesthesia. A highly significant correlation was found
between $V_{O_2}$ and body weight which may be useful in situations where $V_{O_2}$ is not
easily measured.

Oxygen uptake has been measured in congenital heart disease in sedated infants breathing sponta-
neously via an open circuit (Cayler, Rudolph and Nadas, 1963; Lees, Way and Ross, 1967),
and in awake infants by closed circuit (Levison, Delivoria-Papodopoulos and Swyer, 1965).

Neither method is suitable during general anaesthesia, the open circuit destroys the char-
acteristics of the T-piece circuit, and the closed circuit spirometric method cannot be used in the
presence of nitrous oxide, because the uptake of this gas cannot be distinguished from oxygen
uptake.

There is little justification in assuming oxygen uptake values, since these are rarely basal during
general anaesthesia (Nunn, Bergman and Coleman, 1965).

We have therefore devised a circuit which attempts to overcome these objections and this paper reports its use during general anaesthesia with controlled ventilation in twelve infants with congenital heart disease ranging in age from
10 days to 4 years, studied during cardiac catheterization.

METHOD

The closed circuit.

The circuit is shown in figure 1 and consists of the following features.

A 5-litre glass bottle in which is suspended a rubber bag which can be opened to the ambient
atmosphere. The bottle serves as a reservoir for the anaesthetic mixture (30 per cent oxygen +
70 per cent nitrous oxide). The bag functions as a (dry) spirometer bell permitting the patient to
breathe into and out of an otherwise rigid circuit. When the circuit pump is operating there is
a slight negative pressure in the bottle, ensuring that the bag is always partially inflated. The bag
moves with the patient's ventilation and expands as oxygen and nitrous oxide are removed from
the circuit by the patient.

The circulating pump is leakproof and is able to deliver a flow of 10 l./min measured with a
Rotameter and to develop a pressure of 10 Lb./sq.in. The output therefore closely resembles
that of the Boyle machine.

The pump output is delivered to what is in effect a modified Ayre T-piece fitted to a double-
ended bag on the exhaust limb and the discharge from this bag is returned to the circuit.
The carbon dioxide produced by the patient is absorbed by soda-lime. Part of the circuit flow
(100 ml/min) is diverted through a paramagnetic oxygen meter, being first dried by silica gel. The
tap system connecting the patient to the circuit has provision for a rapid switch-over to an
external T-piece by which ventilation can be continued from an independent anaesthetic
machine should there be a circuit malfunction.

There is a further four-way tap, turning the circuit into an open circuit, enabling the
apparatus to be flushed out with anaesthetic mixture.
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Fig. 1

Closed circuit devised for measurement of \( V_{O_2} \) during IPPV in infants.

**Derivation of formulae.**

\( V_M = \) Volume of closed circuit in ml (ATPS).

\( V_F = \) FRC in ml (STPD).

\( V_B = \) Volume of air in bag (ml STPD) at end of experiment

= total volume of oxygen and nitrous oxide absorbed.

\( T = \) Duration of experiment (min)

= time of absorption.

\( t_1 = \) Initial temp (°C) of circuit gas (time zero).

\( t_2 = \) Final temp (°C) of circuit gas (time \( T \)).

\( K_a = \) Factor converting ATPS to STPD at temp \( t_1 \) °C.

\( K_b = \) Factor converting ATPS to STPD at temp \( t_2 \) °C.

\( Y_1 = \) Initial oxygen concentration in circuit gas.

\( Y_2 = \) Final oxygen concentration in circuit gas.

\( X_1 = \) Initial oxygen concentration in alveolar gas.

\( X_2 = \) Final oxygen concentration in alveolar gas.

\( V_O_2 = \) Oxygen uptake rate (ml/min STPD).

\( V_{O_2} = \) Oxygen uptake volume absorbed in time \( T \).

\( V_A = \) Alveolar ventilation rate (ml/min STPD).

The term \( V_F (X_1 - X_2) \) represents the unmeasurable oxygen storage in the lung and constitutes only about 2 per cent of the measured oxygen uptake. In the section in which errors are discussed it will be shown that this quantity can be written with sufficient accuracy as \( V_F (Y_1 - Y_2) \).

The basic formula for rate of oxygen uptake (\( \dot{V}_{O_2} \)) is therefore:

\[
\dot{V}_{O_2} = \frac{V_M K_a Y_1 + V_F (Y_1 - Y_2) - (V_M - V_B) K_b Y_2}{T}
\]

If, as is likely, the temperature rise during the experiment is not greater than 1°C, then it is possible to use the mean or initial temperature with an appropriate single gas factor (\( K \)), using a simpler formula:

\[
\dot{V}_{O_2} = \frac{(K V_M + V_F) (Y_1 - Y_2) + V_B K Y_2}{T}
\]

This formula was used to calculate oxygen uptake reported in this paper and it will be underestimated by not more than 3 per cent (see discussion of errors) due to this simplification.
It will also be shown later that it is sufficiently accurate to estimate \( V_F \) by the formula:

\[
V_F = 25 \times \text{body weight in kg (Comroe, 1966)}
\]

CIRCUIT PREPARATION

Leaks.

The circuit was tested for leaks at pressures of \( \pm 30 \) cm of water, using a water manometer. No leaks were found over a test period of 20 minutes.

Calibration of paramagnetic oxygen meter.

A tap system allowed calibrated gases to be passed through this meter. The instrument was zeroed using white spot nitrogen and the “span” adjusted to give 20.9 per cent oxygen with room air. The meter is insensitive to nitrous oxide (Nunn et al., 1964).

Dry spirometer zero.

The “dry spirometer” bag was flattened using the 100-ml calibrated syringe which was later used to measure the air content of this bag. After flattening the bag it was sealed using the tap provided.

Filling the circuit.

In the open circuit position the circuit was flushed with 30 per cent oxygen and 70 per cent nitrous oxide for 4–5 minutes. Towards the end of this time the flow was stopped, a closed circuit was restored and the pump turned on to ensure mixing of circuit gases. After a few minutes mixing the pump was turned off and an oxygen reading was taken. If the reading was not less than 30 per cent flushing was judged to be adequate, but the pump was turned on again to check whether the circuit gases were thoroughly mixed. The apparatus was ready when consecutive readings differed by less than 0.1 per cent oxygen.

PATIENTS

Premedication.

Premedication consisted of atropine, 0.1–0.6 mg by intramuscular injection. In infants over 1 year morphine 0.33 mg/kg was added.

Induction.

General anaesthesia was induced by intravenous injection of 2.5 per cent sodium thiopentone, 4 mg/kg body weight, and neuromuscular paralysis was achieved by intravenous injection of tubocurarine 0.6 mg/kg. The trachea was intubated with a closely-fitting rubber endotracheal tube (Magill) and the pharynx and oropharynx filled with sterile water. The lungs were manually hyperinflated using the external T-piece (fig. 1) with 30 per cent oxygen and nitrous oxide to a tracheal pressure of 35–40 cm H\(_2\)O displayed on an oscilloscope as the amplified signal of a calibrated pressure transducer connected to the airway. If bubbles appeared in the pharynx, indicating a leak, reintubation was performed with a closer-fitting tube and the test repeated.

Maintenance of general anaesthesia.

Anaesthesia was maintained with 30 per cent oxygen and nitrous oxide through an added deadspace of 1.5 ml/kg body weight, using a fresh gas flow of 9 l./min. Respiratory rates of 100–120 b.p.m. were used by the same anaesthetist, in each study. Tubocurarine was added as required in incremental doses of one-eighth of the initial dose.

Patient body temperature.

Patients were studied lying supine on the X-ray table. The probe of an oesophageal thermometer was placed in the middle third of the patient’s oesophagus and temperature monitored throughout the study. Patients aged less than 6 months were wrapped in gauze wool. No attempt was made to conduct a study under basal conditions or in a neutral thermal environment, room temperature being 20–22°C throughout the studies.

Study procedure.

Oxygen uptake measurements were made over 3–15 minutes, and in each patient an attempt was made to obtain a comparable drop in the concentration of oxygen of approximately 3 per cent from its initial value \((Y_i)\). With the circuit pump off and the dry spirometer bag open to atmosphere, the patient’s lungs were allowed to expire passively to functional residual volume for 3 sec, and then connected to the closed circuit. The pump was immediately switched on and ventilation was maintained manually by the circuit anaesthetic...
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At the end of the period of measurement ($\Delta T$) the patient's lungs were again allowed to expire to functional residual volume and the patient ventilated via the external T-piece. After allowing 3-4 minutes for the circuit gas to mix, the pump was shut off and the final oxygen concentration ($Y_f$) was read. The volume in the circuit anaesthetic bag was displaced into the bottle and the contents of the dry spirometer bag (VB) isolated. This volume was then measured using the glass syringe. The circuit temperature was recorded.

The circuit was refilled in readiness for the next measurement.

RESULTS

The results obtained from a study of oxygen uptake are shown in Table I.

<table>
<thead>
<tr>
<th>Pt. No.</th>
<th>Diagnosis</th>
<th>age</th>
<th>Wt. (kg)</th>
<th>$F_{102}$ Initial</th>
<th>$F_{102}$ Final</th>
<th>Volume dry spirometer (ml)</th>
<th>Temperature ($^\circ$C)</th>
<th>$\Delta T$ (min)</th>
<th>$V_{O_2}$ (ml/min/kg) STPD (mean)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 VSD</td>
<td>3 m</td>
<td>3.7</td>
<td></td>
<td>0.336</td>
<td>0.276</td>
<td>863</td>
<td>37.5</td>
<td>26</td>
<td>15.0 (10.25)</td>
</tr>
<tr>
<td>2 Tetralogy of Fallot</td>
<td>3 y</td>
<td>14.2</td>
<td></td>
<td>0.348</td>
<td>0.318</td>
<td>340</td>
<td>37.0</td>
<td>25</td>
<td>3 (6.30)</td>
</tr>
<tr>
<td>3 Tetralogy of Fallot</td>
<td>4 y</td>
<td>15.2</td>
<td></td>
<td>0.315</td>
<td>0.279</td>
<td>620</td>
<td>37.0</td>
<td>24</td>
<td>5 (6.30)</td>
</tr>
<tr>
<td>4 VSD and PDA</td>
<td>2 m</td>
<td>3.8</td>
<td></td>
<td>0.337</td>
<td>0.303</td>
<td>407</td>
<td>37.5</td>
<td>25</td>
<td>10.0 (8.25)</td>
</tr>
<tr>
<td>5 PDA</td>
<td>8 m</td>
<td>6.9</td>
<td></td>
<td>0.329</td>
<td>0.286</td>
<td>728</td>
<td>38.0</td>
<td>25</td>
<td>7 (9.20)</td>
</tr>
<tr>
<td>6 ASD, VSD, TGV</td>
<td>4 m</td>
<td>4.1</td>
<td></td>
<td>0.323</td>
<td>0.295</td>
<td>377</td>
<td>37.5</td>
<td>24</td>
<td>7 (8.67)</td>
</tr>
<tr>
<td>7 TGV</td>
<td>2½ y</td>
<td>10.0</td>
<td></td>
<td>0.343</td>
<td>0.255</td>
<td>1206</td>
<td>37.5</td>
<td>24</td>
<td>7 (8.10)</td>
</tr>
<tr>
<td>8 Dextrocardia TGV</td>
<td>1 y</td>
<td>9.5</td>
<td></td>
<td>0.347</td>
<td>0.318</td>
<td>705</td>
<td>36.0</td>
<td>24</td>
<td>5 (7.20)</td>
</tr>
<tr>
<td>9 Endocardial fibroelastosis</td>
<td>5 m</td>
<td>6.4</td>
<td></td>
<td>0.335</td>
<td>0.302</td>
<td>1081</td>
<td>37</td>
<td>24</td>
<td>6 (9.37)</td>
</tr>
<tr>
<td>10 VSD TGV</td>
<td>10 d</td>
<td>2.7</td>
<td></td>
<td>0.328</td>
<td>0.307</td>
<td>352</td>
<td>38.5</td>
<td>24</td>
<td>15 (5.40)</td>
</tr>
<tr>
<td>11 Abnormal pulmonary vasculature</td>
<td>7 y</td>
<td>14.5</td>
<td></td>
<td>0.334</td>
<td>0.311</td>
<td>390</td>
<td>38</td>
<td>24</td>
<td>3 (5.10)</td>
</tr>
<tr>
<td>12 PDA</td>
<td>2 m</td>
<td>3.4</td>
<td></td>
<td>0.335</td>
<td>0.295</td>
<td>359</td>
<td>37.5</td>
<td>25</td>
<td>10 (8.37)</td>
</tr>
</tbody>
</table>

VSD=ventricular septal defect. PDA=patent ductus arteriosus. ASD=atrial septal defect. TGV=transposition of the great vessels.

d=days. m=months. y=years.
Oxygen uptake.
The mean oxygen uptake for each patient is shown plotted against body weight (fig. 2), and in eleven patients there was a highly significant correlation between body weight and oxygen uptake as shown by the regression equation $\dot{V}O_2/\text{kg} = 10.2 - 0.273 \times (\text{body wt in kg})$. (Correlation coefficient = -0.83, SEE = 0.81, $t = 4.5$).

![Graph showing oxygen uptake plotted against body weight](image)

Fall in oxygen concentration.
Over the time $\Delta T$ (table I) of a study, the fall in inspired oxygen concentration was of the order of 2-4 per cent but in patient No. 1 the fall was 6 and 7 per cent. The greatest fall was 9 per cent in patient No. 7.

Dry spirometer volume.
These ranged from 0.25 l. to 1.206 l. and were largest during the first measurement and in those patients with the highest oxygen uptake/kg/min.

Circuit temperature.
The temperature of the circuit gas did not rise by more than 1°C so that a mean temperature was used to correct gas volumes to a standard, temperature pressure, dry (STPD) (table I).

DISCUSSION
Lung volume and pulmonary ventilation.
An attempt was made to keep the initial and final resting respiratory levels the same, and although neither lung volume nor pulmonary ventilation was measured we have assumed that both remained constant throughout an estimation. It must be stressed that small variations in these introduce only minor errors in the estimation of $\dot{V}O_2$. If the resting respiratory level changed between the start and end of a study there would be uncertainty about the amount of oxygen stored in the functional residual volume (VR).

Change of resting respiratory level.
Care was taken to allow the subject's lungs to relax for about 3 seconds before switching into or out of the circuit. It is unlikely that VR changed between the beginning and end of the experiment but if, for the sake of argument, it had increased by an amount $\Delta VR$ then VB would be increased by an amount $\Delta VR$. Thus, the amount of oxygen stored in the lung would be underestimated by an amount $\Delta VR$ and the amount in the circuit overestimated by $\Delta VR$. The total overestimation would be $\Delta VR(Y_2 - X_2)$.

From equation (6) below

$$Y_2 - X_2 = \frac{\dot{V}O_2}{\dot{V}A}[1 - F_{102}(1 - K)]$$

so that $Y_2 - X_2$ is not greater than $\dot{V}O_2/\dot{V}A$, that is, not greater than about 0.05. VR varies from about 80 ml to 400 ml so that if VR changed by 5 per cent $\Delta VR$ would change by between 4 ml and 20 ml. Thus, depending on the sign of VR, $\dot{V}O_2$ would be over- or underestimated by between 0.2 and 1 ml. But the total oxygen uptake is about 300 ml, so that the error in $\dot{V}O_2$ would not be greater than 0.3 per cent.

Estimation of VR ($X_1 - X_2$).
One form of alveolar ventilation equation is:

$$F_{A02} = F_{102} [1 + \frac{\dot{V}O_2}{\dot{V}A}(1 - K)] - \frac{\dot{V}O_2}{\dot{V}A} \quad (6)$$

Therefore, in our terminology ($X = F_{A02}$ and $Y = F_{102}$):

$$X_1 - X_2 = (Y_1 - Y_2) [1 + \frac{\dot{V}O_2}{\dot{V}A}(1 - K)] \quad (7)$$

Where, in our case, $K = (\dot{V}O_2 - \dot{V}N_2)/\dot{V}O_2$. K can vary in value from zero to unity so that if $\dot{V}O_2/\dot{V}A$ is about 0.05 then $[1 + \frac{\dot{V}O_2}{\dot{V}A}(1 - K)]$ will vary from unity to about 1.05. Thus, if...
\( \text{VF}(X_1 - X_2) \) is written as \( \text{VF}(Y_1 - Y_2) \) the error will not exceed 5 per cent. But \( \text{VF}(Y_1 - Y_2) \), the change in oxygen content of the lung, has a value of between 1 and 3 per cent of the total oxygen taken up, depending on the size of the FRC, so that equating \( (X_1 - X_2) \) with \( (Y_1 - Y_2) \) will underestimate \( V_o \) at the most by 5 per cent of 3 per cent, which is negligible.

Similarly if the estimate of \( \text{VF} \), based on the regression \([\text{VF} = 25 \times \text{body weight (kg)}]\) were in error by as much as 20 per cent the resulting error in \( V_o \) would lie between 20 per cent of 1 per cent and 20 per cent of 3 per cent, that is an error of between 0.2 and 0.6 per cent.

The measurement of oxygen concentration.

Circuit oxygen concentrations are reported in table I to the nearest 0.1 per cent oxygen, but the oxygen analyzer can be and was read to the nearest 0.05 per cent oxygen and calculations were made accordingly.

Thus, the 3 per cent oxygen span \( (Y_1 - Y_2) \) can be in error by \( \pm 0.05 \) per cent oxygen. This span determines the estimate of about two-thirds of the total oxygen uptake so that the error in \( V_o \) will be about \( \pm 1 \) per cent.

Temperature.

The temperature of the circuit gases was surprisingly stable. In two experiments the temperature rose by 1°C. In the other the rise was not greater than 0.5°C.

When the temperature changed, a mean value was used to calculate \( K \), the factor converting ATPS to STPD.

From equation (2) we can derive the error due to the assumption that \( K = \frac{1}{2}(K_1 + K_2) \). It is given by:

\[
\frac{1}{2}(K_1 - K_2) \left[ \text{VMT}(Y_1 + Y_2) - \text{Vb} \cdot Y_2 \right]
\]

(8)

\( V_o \) will be underestimated by this amount and, for the maximum rise of 1°C, is about 3 per cent of the total oxygen uptake and therefore about 1\( \frac{1}{2} \) per cent for the mean rise.

Discussion of error assessment.

In so far as it is valid to summate the errors listed, it would seem that we may have underestimated our oxygen uptakes by not more than 5 per cent.

If allowance had been made for temperature changes the error would have been about \( \pm 2 \) per cent. It would be shortsighted to strain for greater accuracy unless there were also careful control of environmental temperature and other factors controlling the physical and metabolic state of the patient.

Oxygen uptake.

Clearly there are pitfalls in comparing our values for oxygen uptake (fig. 2) with those of other workers, mainly because of the different circumstances in which measurements were made. But figures for oxygen uptake measured by open circuit (Cayler, Rudolph and Nadas, 1963; Lees, Way and Ross, 1967), and closed circuit (Levison, Delivoria-Papodopoulos and Swyer, 1965) in non-anaesthetized infants indicate that over the range of body weight of 2–5 kg the temperature gradient between patient and environment is of crucial importance.

Levison, Delivoria-Papodopoulos and Swyer (1965) carefully studied their babies in a neutral thermal environment and found a mean oxygen uptake of 7.7 ml/kg/min (STPD) for a mean body weight of 2.7 kg (fig. 2A). This figure is well below 9.4 ml/kg/min (STPD) derived from extrapolation of our regression line (fig. 2) from patients studied in the environment of a cardiac catheterization suite. It suggests that our smaller patients were defending their body temperature at the expense of an increased oxygen uptake. Levison's series consisted of infants with \( P_{ao} \) levels of 38–72 mm Hg and it might be that the low figure for \( V_o \) which they obtained reflected the hypoxaemia of their patients.

Lees, Way and Ross (1967) studied a group of infants with a mean body weight almost double that of the patients of Levison and colleagues, and our regression line predicts a mean \( V_o \) of 8.9 ml/kg/min (STPD) (fig. 2B) against Lees and colleagues' measured figure of 8.5 ml/kg/min (STPD) (fig. 2B) obtained under study conditions, very similar to our own.

We are unable to find figures in the literature with which to compare our own values for \( V_o \) during general anaesthesia involving IPPV in infants, but previous work on the experimental animal (Owen-Thomas et al., 1970) failed to show a significant difference between \( V_o \) during general anaesthesia with spontaneous breathing compared
to general anaesthesia during IPPV which suggests that anaesthesia itself with or without IPPV tends to have little effect on $V_{O_2}$. Further work on this point is clearly needed in infants with congenital heart disease.

Patient No. 10, a 10-day-old infant weighing 2.7 kg had a mean oxygen uptake of only 5.4 ml/kg/min. This is 57 per cent below predicted oxygen uptake from the above regression equation and the figure is not easily explained, but might be associated with the gross metabolic acidosis which was noted in this infant prior to the study.

REFERENCES


SOCiETY OF ANAESTHETIC LABORATORY TECHNICIANS

There will be a Scientific Meeting of the Society of Anaesthetic Laboratory Technicians at the Nuffield Department of Anaesthetics, Radcliffe Infirmary, Oxford, on Friday and Saturday, October 1 and 2, 1971, commencing at 14.00.

All members should have been notified but any other person interested in attending or requiring further information should contact Mr J. B. Thompson at the Radcliffe Infirmary.