COMPARISON OF VENTILATION AND GAS EXCHANGE IN ANAESTHETIZED INFANTS AND CHILDREN DURING SPONTANEOUS AND ARTIFICIAL VENTILATION

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Measurements of minute and alveolar ventilation (VE and VA), respiratory frequency, end-tidal carbon dioxide concentration (E'CO₂), deadspace (Vb) and carbon dioxide output (VCO₂) were made in 22 anaesthetized infants and young children during spontaneous (SV) and intermittent positive pressure ventilation (IPPV). In the children who had been given an opioid premedication, E'CO₂ concentrations were significantly greater during SV than the predetermined value set for IPPV. In infants premedicated with atropine alone, E'CO₂ during SV was only slightly greater than during IPPV, and VA was not changed. A mean tidal volume (Vt) of 9.8 ± 2.5 ml kg⁻¹, and a mean VE of between 225 and 250 ml min⁻¹ kg⁻¹, were required to produce E'CO₂ 4.5% during IPPV. Despite a decrease in respiratory frequency, Vb/Vt and Vb per minute were both decreased by IPPV in infants. VCO₂ was unchanged in both groups. The decrease in wasted ventilation seen during IPPV in infants supports its use in clinical practice.

Opinions are divided about the relative merits of spontaneous and artificial ventilation during anaesthesia in infants and young children. Opponents of artificial ventilation cite the unnecessary complexity of the technique, whilst its advocates suggest that it ensures adequate ventilation and increases functional residual capacity.

This paper compares measurements of ventilation and gas exchange during spontaneous ventilation in a group of infants and young children with measurements taken subsequently in the same children during artificial ventilation.

PATIENTS AND METHODS

Minute ventilation (VE), respiratory frequency (f), end-tidal carbon dioxide concentration (E'CO₂) (%) and mixed expired carbon dioxide fraction (FE.CO₂) were measured during surgery in 22 anaesthetized infants and children during spontaneous ventilation (SV), and then during intermittent positive pressure ventilation (IPPV). Alveolar ventilation (VA), deadspace minute ventilation (Vb), deadspace/tidal volume ratio (Vd/VT), carbon dioxide output (VCO₂) were calculated. The ages of the patients ranged from 4 weeks to 5 yr and their body weights (bw) from 3.7 to 17.9 kg. All patients were free from cardiorespiratory disease. Surgery consisted of elective abdominal, genito-urinary and ophthalmic procedures. No patient had lost a significant quantity of blood at the time of the study.

All patients fasted for 4–5 h before surgery. Thirteen patients (mean bw 6.9 ± 3.3 kg) were premedicated with atropine 0.2–0.4 mg i.m. alone; 11 were younger than 1 yr of age and all were less than 10 kg in weight. Nine patients (mean bw 14.5 ± 2.8 kg) received premedication which included an opioid analgesic; all were older than 1 year and all weighed more than 10 kg. Children between 10 and 15 kg bw received Pethidine Compound 0.07 ml kg⁻¹ (1 ml contained: pethidine 25 mg, promethazine 6.25 mg and chlorpromazine 6.25 mg) and atropine i.m. 1h before surgery. Children heavier than 15 kg received papaveretum 0.4 mg kg⁻¹ and hyoscine 0.008 mg kg⁻¹ i.m. 1.5 h before surgery.

Anaesthesia was induced with cyclopropane in oxygen (FIO₂ 0.5). Suxamethonium 1–1.5 mg kg⁻¹ was administered i.v. and the trachea intubated. Spontaneous breathing was resumed and anaesthesia maintained with nitrous oxide and 0.5–2% halothane in oxygen (FIO₂ 0.5).

The characteristics of the non-rebreathing anaesthetic system (derived from the AMBU Paedi-

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Anaesthesia system, the measurement and recording systems and their calibration for \( V_E \), \( V_T \), \( f \), \( E'CO_2 \) and \( VC02 \) have been described in the preceding paper (Lindahl, Hulse and Hatch, 1984). During intermittent positive pressure ventilation at a peak airway pressure of 15 cm H\(_2\)O, the measurement of tidal volume was decreased by less than 5% when measured against volumes determined plethysmographically.

The anaesthetist in charge of the patient was not involved in the study and was at liberty to control the depth of anaesthesia as he saw fit. No measurements were made until anaesthesia was considered stable clinically, the halothane concentration was constant and at least 20 min had elapsed since induction of anaesthesia (Salanitre and Rachow, 1976). After the initial series of measurements had been obtained, tubocurarine 0.4 mg kg\(^{-1}\) was administered, and IPPV commenced by connecting a Nuffield 200 ventilator to the system in place of the reservoir bag. The I:E ratio was set at 1:1.5, giving a frequency of 24 b.p.m. and the tidal volume was adjusted to achieve \( E'CO_2 \) 4.5%. Measurements were repeated 20 min after the change to controlled ventilation. In eight patients, heart rate and arterial pressure were recorded at 1-min intervals throughout the study (Dinamap 847).

Calculations

Deadspace values were divided into total deadspace (\( VD^{total} \) (ml) (including all apparatus deadspace) and net deadspace (\( VD^{net} \) (ml) by subtraction of 9 ml for apparatus deadspace. \( V_E \), \( V_A \), \( V_T \), \( V_D \), and \( V_D \) were corrected to body temperature and pressure saturated (BTPS), \( VCO_2 \) values to ambient temperature and pressure saturated (ATPS). The following formulae were used:

\[
\begin{align*}
VCO_2 (ml \text{ min}^{-1}) &= \frac{\text{gas collection } V_E \times FECO_2}{100} \\
V_A (ml \text{ min}^{-1}) &= \frac{VCO_2 \times 100}{E'CO_2} \\
V_D (ml \text{ min}^{-1}) &= V_E - V_A \\
V_D (ml) &= \frac{V_D}{f}
\end{align*}
\]

Statistics

Mean values and standard deviation (SD) were calculated. Linear regressions and covariance analysis were performed and paired Student's \( t \) tests applied to the mean data.

RESULTS

End-tidal carbon dioxide concentration and alveolar ventilation

In the younger patients premedicated with atropine alone, \( E'CO_2 \) (mean ± 1SD) decreased from 5.4 ± 1.2% during SV to 4.7 ± 0.5% during IPPV (\( P < 0.05 \)) (fig. 1). In the older patients receiving an opioid premedication, the corresponding decrease in \( E'CO_2 \) was from 6.9 ± 1.0% to 4.5 ± 0.4% (\( P < 0.001 \)) (fig. 1).

The younger patients premedicated with atropine alone had \( VA \) of the same magnitude during spontaneous and controlled ventilation (fig. 1). In the opioid group the decreased \( E'CO_2 \) was reached at a
greater alveolar ventilation \((P < 0.01)\) (fig. 1). The regression equation for \(VA\) during IPPV for all patients was \(VA = 151 \times \text{kg}^{-2} - 20\), \(r = 0.84\). The mean (±1 SD) for \(VA\) was: 148 ± 43 ml min\(^{-1}\) kg\(^{-1}\).

**Minute ventilation**

In the atropine group, the mean value (±1 SD) for \(VE\) was decreased from 1980 ± 608 ml min\(^{-1}\) during SV to 1658 ± 855 ml min\(^{-1}\) during IPPV (n.s.) (fig. 2). In those patients who received opioid premedication, the mean value (±1 SD) for \(VE\) was increased from 2154 ± 513 ml min\(^{-1}\) during SV to 2917 ± 927 ml min\(^{-1}\) with IPPV \((P < 0.05)\) (fig. 2).

The relationship between \(VE\) and body weight for all patients during IPPV followed the equation: \(VE = 210 \times \text{kg} + 170\), \(r = 0.92\). The mean value (±1 SD) for \(VE\) was 224 ± 52 ml min\(^{-1}\) kg\(^{-1}\).

**Respiratory rate and tidal volume**

In both groups, the respiratory rate during SV was significantly faster than that set for IPPV \((P < 0.001)\) (fig. 3). In both groups \(VT\) was smaller during SV than IPPV \((P < 0.001)\) (fig. 3).

The regression equation to the relationship between \(VT\) and body weight (kg) was \(VT = 9.1 \times \text{kg} + 5.1\), \(r = 0.86\) during IPPV. The mean value (±1 SD) for \(VT\) was 9.8 ± 2.5 ml kg\(^{-1}\).

**Carbon dioxide output**

The elimination of carbon dioxide per minute was similar during SV and IPPV (fig. 2). The relationship between \(VCO_2\) and body weight during IPPV \((n = 22)\) was expressed by the equation:

\[ VCO_2 = 6.2 \times \text{kg} + 0.70, \quad r = 0.86. \]

There was an almost direct proportionality between \(VCO_2\) and body weight during IPPV with a mean value (±1 SD) of 6.3 ± 1.5 ml min\(^{-1}\) kg\(^{-1}\).

**Deadspace**

In the younger patients (premedicated with atropine alone) deadspace ventilation per minute \((V_{D_{tot}})\) was decreased during IPPV \((P < 0.05)\) while it was unchanged between the two modes of ventilation in the opioid group (fig. 4). During IPPV, deadspace per breath \((V_{D_{breath}})\) was greater than during SV (fig. 4) in the atropine group \((P < 0.01)\) and the opioid group, although in the latter group the difference was not significant. The mean ratio of \(V_{D_{tot}}\) to \(VT\) (±1 SD) in the atropine group decreased from 0.49 ± 0.14 during SV to 0.38 ± 0.10 during IPPV \((P < 0.05)\) (fig. 4). In the opioid group, this ratio decreased from 0.44 ± 0.05 during SV to 0.28 ± 0.11 during IPPV \((P < 0.001)\) (fig. 4).

![Fig. 4. Mean values (±1 SD) for total deadspace minute ventilation \((V_{D_{tot}})\), total deadspace \((V_{D_{breath}})\) and \(V_{D_{tot}}/VT\) ratio in the atropine group (open circles) and the opioid group (closed circles).](/content/fig.jpg)
Heart rate and arterial pressure

There were no significant differences in heart rate or arterial pressure during spontaneous ventilation compared with those obtained during IPPV in the eight patients in whom the Dinamap recorder was used.

DISCUSSION

End-tidal carbon dioxide concentration and alveolar ventilation

In the younger patients premedicated with atropine, \( E'\text{CO}_2 \) during spontaneous ventilation was low and only had to be decreased by an average of 0.7% to reach the desired value during IPPV. It is unlikely that the low end-tidal carbon dioxide concentration during SV was the result of inaccurate measurements at the high respiratory rates sometimes found since, in all patients, an end-tidal carbon dioxide plateau phase was reached, suggesting that the response time of the carbon dioxide meter was adequate at respiratory rates up to 80 b.p.m. As might be expected from the small difference in \( E'\text{CO}_2 \) between SV and IPPV in the younger patients, \( VA \) was similar with the two forms of ventilation.

The higher end-tidal carbon dioxide concentration during SV in the older patients was probably a result of the opioid premedication used in this age group, and has been discussed previously (Lindahl, Wallgren and Wahlén, 1966) found that a tidal volume of 10 ml kg\(^{-1}\) at a rate of 20 b.p.m., resulted in a capillary carbon dioxide tension of 4.7 kPa, and Lindahl, Okmian and Thomson (1979) used a tidal volume of 12 ml kg\(^{-1}\) at a rate of 20 b.p.m. to obtain a mean arterial carbon dioxide tension of 3.7 kPa.

Minute ventilation

In a previous study the average minute ventilation, measured in anaesthetized adult patients, was increased by approximately 130% during mechanical as compared with spontaneous ventilation, resulting in a decrease in arterial carbon dioxide tension by 0.7 kPa (Bindslev et al., 1981). In the present study \( VE \) was higher during IPPV in the older patients receiving opioid premedication and the average minute volume required to decrease \( E'\text{CO}_2 \) by 2.4% was 135% higher than that during SV \((P < 0.05)\) (fig. 2). However, in the younger age group, the decrease in mean \( E'\text{CO}_2 \) by 0.7% during IPPV was achieved at a minute volume which was not significantly lower than that during SV. This suggests that there was considerable wasted ventilation during spontaneous breathing in these younger patients, possibly because of the relatively high apparatus deadspace in this group, and high respiratory frequency during SV.

The tidal volumes reported during IPPV compare well with previously published standards for artificial ventilation in infants and children. Okmian, Wallgren and Wahlén (1966) found that a tidal volume of 10 ml kg\(^{-1}\) at a rate of 20 b.p.m., resulted in a capillary carbon dioxide tension of 4.7 kPa, and Lindahl, Okmian and Thomson (1979) used a tidal volume of 12 ml kg\(^{-1}\) at a rate of 20 b.p.m. to obtain a mean arterial carbon dioxide tension of 3.7 kPa.

Carbon dioxide output

Carbon dioxide production for the whole group was of the same magnitude during SV and IPPV as found in a previous study by Bain and Spoerel (1976). The value of 6.3 ± 1.5 ml min\(^{-1}\) kg\(^{-1}\) for carbon dioxide output during controlled ventilation in children was in agreement with that published by Nightingale and Lambert in 1978.

The similarity in carbon dioxide production suggests that the metabolic state was similar during SV and IPPV. A higher metabolic rate might have been expected in the 13 younger patients premedicated with atropine alone than in the nine who received a narcotic. In fact, in 10 of the 13 patients in the atropine group, \( V\text{CO}_2 \) was lower during IPPV than SV, although the difference between the two groups just failed to reach significance.

Deadspace ventilation

The high deadspace ventilation per minute during SV in small children was most probably attributable to their high respiratory frequencies; it was significantly decreased by controlled ventilation, although deadspace per breath was increased. In the older patients \( V_D \) was unchanged between the two modes of ventilation (fig. 4).

The importance of respiratory frequency for ven-
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COMPARACION DE LA VENTILACION ET DES ECHANGES GAZEUX CHEZ DES NOUVEAU-NES ET DES ENFANTS EN VENTILATION ARTIFICIELLE OU SPONTANEE

RESUME

Des mesures de la ventilation alvéolaire et de la ventilation minute (VA et Vb), de la fréquence respiratoire, de la concentration de dioxyde de carbone de fin d’expiration (E’CO2), de l’espace mort (Vb) et du débit de dioxyde de carbone (VO2) ont été faites chez 22 nouveau-nés et nourrissons anesthésiés en ventilation spontanée (VS) et en ventilation en pression positive intermittente (VPPI). Chez les enfants qui avaient reçu une prémédication par les opiaces, les E’CO2 étaient significativement plus élevées au cours de la VS que le niveau prédéterminé pour la VPPI. Chez les enfants prémédiqués à l’atropine seule, la VS était beaucoup plus supérieure à celle obtenue en VPPI, et le VE n’était pas modifiée. Pour obtenir une E’CO2 de 4,5% en VPPI, il fallait un volume courant moyen (VT) de 9,8 ± 2,5 ml kg⁻¹ et une VE moyenne entre 225 et 250 ml min⁻¹ kg⁻¹. Malgré une diminution de la fréquence respiratoire, VE/VT et VO₂ par minute étaient tous deux diminués par la VPPI chez les nouveau-nés. La VO₂ était inchangée dans les deux groupes. La diminution de ventilation non utile, vue en VPPI chez les nouveau-nés, justifie l’utilisation de cette technique en pratique clinique.

COMPARACION DE VENTILACION E INTERCAMBIO DE GASES EN CRIATURAS Y NIÑOS ANESTESIADOS DURANTE VENTILACION ESPONTANEA Y ARTIFICIAL

SUMARIO

En 22 criaturas y niños anestesiados, se llevaron a cabo mediciones de la ventilación respiratoria y alveolar (Vb y VA), de la frecuencia respiratoria, de la concentración de anhídrido carbónico respiratorio-terminal (E'CO2), del espacio muerto (Vb) y de la salida de anhídrido carbónico (VO2) durante ventilación espontánea (SV) y ventilación por presión positiva intermitente (IPPV). En los niños que habían recibido premedicaciones opiáceas, las concentraciones de E'CO2 eran mucho más altas durante la SV que el valor predeterminado establecido para la IPPV. En las criaturas que habían recibido premedicación con atropina sola, el E'CO2 durante la SV sólo alcanzaba valores ligeramente superiores a las registradas durante la IPPV y el VA no sufrió cambios. Eran necesarios un volumen respiratorio (VT) de 9,8 ± 2,5 ml kg⁻¹ y un VE promedio de entre 225 y 250 ml min⁻¹ kg⁻¹ para obtener una concentración E'CO2 de 4,5% durante la IPPV. A pesar de un descenso en la frecuencia respiratoria, el VE/VT y el VO₂ por minuto bajaron ambos bajo la influencia del IPPV en las criaturas. En ambos grupos, el VO2 no se alteró. El descenso de la ventilación residual registrada durante la IPPV en criaturas milita a favor de su uso en casos clínicos.