SUMMARY

The Siemens-Elema CO2 Analyzer 930 allows calculation of carbon dioxide elimination from the instantaneous measurement of expired gas flow (VE) and carbon dioxide fraction (FECO2). VE is measured in the ventilator and FECO2 at the Y-piece. The most important source of error in the measurement of carbon dioxide elimination is rebreathing, which corresponds to about 24 ml of end-expiratory gas per breath with the standard Y-piece and tubing. This problem may be decreased by the use of non-return valves in the Y-piece. Allowance must be made for the effects of intermolecular interaction between carbon dioxide and the carrier gas, as the reading is about 20% greater with nitrous oxide than with oxygen. This problem can be largely circumvented by calibration with appropriate gas mixtures. Errors resulting from analyser delay are small, and are eliminated completely by the inclusion of fast electronic components. Carbon dioxide analysis is linear with air as carrier gas, but slightly a linear with nitrous oxide in oxygen mixtures. This error can be minimized by using calibration gases with a carbon dioxide content close to that of expired gas. The expiratory flow meter is linear if kept in good condition. Variations in temperature and water content of expired gas cause overestimation of mean expired carbon dioxide fraction (FECO2) by a factor of 1.01—1.02. Compressed gas in the tubing causes a small error which may be neglected at normal airway pressures with tubing of low compliance. Carbon dioxide measurement is slightly affected by barometric pressure. During mechanical ventilation of the lungs in 10 patients with air, FECO2 obtained after corrections for known errors agreed well with Scholander analysis of mixed expired gas.

METHODS

Rebreathing of gas in the tubing

Effects of other gases

Delay in carbon dioxide analysis

Alinearity of carbon dioxide analysis

Alinearity of VE measurement

Variations in temperature and vapour content of expired gas affecting volume correction and FECO2

Release of compressed gas during expiration

Variations in barometric pressure

Analog calculation of tidal carbon dioxide production (VTCO2)

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carbon dioxide-containing gas would then not affect the measured net expired carbon dioxide volume. For practical reasons, however, flow is measured in the ventilator and $F_{\text{CO}_2}$ at the Y-piece, and only during expiration. This means that an unknown volume of carbon dioxide is inspired, causing an overestimation of carbon dioxide elimination. It might be assumed that only the volume between the Y-piece and the window of the cuvette, about 8 ml with standard components, is rebreathed. In fact, expired gas present in the Y-piece and both inspiratory and expiratory tubing at the start of inspiration is rebreathed also.

In order to quantify this, a 3-litre rubber bag containing radioactive xenon was ventilated by the ventilator. The distribution of radioactivity in the tubing distal to the carbon dioxide cuvette was recorded by a gamma-camera taking frames every 0.1 s. The total count rate was obtained at the end of expiration and at the end of inspiration. A decrease of the count rate during inspiration ($D$) was always recorded. This decrease in xenon represents rebreathing of gas from the previous expiration, since the expiratory valve is closed during inspiration. Measurement of the radioactivity of a known volume of the expiratory tubing at end-expiration yielded a count rate per millilitre of end-tidal gas (CR). The amount of rebreathing, expressed as millilitre end-tidal gas could now be estimated as $D/CR$.

**Effects of other gases.** This was assessed by introducing these gases into the cuvette during the inspiratory phase, whilst flushing the cuvette with air during the inspiratory phase. The problem of intermolecular interaction between carbon dioxide and nitrous oxide or oxygen has been investigated by Fletcher (1980) and is briefly reviewed below.

**Analyser delay** has already been investigated by Fletcher (1980). The effect on $FE_{\text{CO}_2}$ was quantified in 10 anaesthetized patients by comparing electronic components with different response times.

**Alinearity of carbon dioxide analysis.** The response to carbon dioxide dispersed in gases having a similar composition to air is linear (Olsson et al., 1980). Linearity was also assessed with test gases containing 1–8% carbon dioxide dispersed in 50% nitrous oxide in oxygen, which were prepared by weighing in compressed gas cylinders, and passed through the carbon dioxide analyser whilst the digital values for end-tidal carbon dioxide were noted. The manufacturer of the test gases (Alfax, Sweden) guaranteed the composition to within 1% of the stated value.

**Alinearity of $\dot{V}E$ measurement.** A Servo ventilator was used to produce accurate constant-flow pulses lasting 2 s, at intervals of 4 s. The test gas, 50% nitrous oxide in oxygen from this ventilator, was directed to the expiratory port of a second Servo ventilator, to be tested, and then through a wet gas meter (Wohlgroth, Zürich), which had been saturated with the test gas. This manoeuvre was made possible by arresting the test ventilator in the expiratory phase, by means of a special modification. The expiratory flow signal was compared with the flow obtained by direct readings from the wet gas meter.

In a different experiment, the cyclically varying gas flow from a strong, electrically powered piston pump was passed through the test ventilator’s expiratory port. Tubing of low resistance was used. The yield of the piston pump, at each phase of the pump cycle, was assessed with a calibrated (with air) Fleisch pneumotachograph. The same stroke volume with different gases was fed to the ventilator to test the effect of the properties of the gases on the measurements of flow.

**Variations in temperature of expired gas** were measured by passing a thermocouple through the tubing during mechanical ventilation in two patients. Measurements were commenced at the distal end of the tracheal tube and continued to the exhaust port of the ventilator. Values presented here were obtained in midstream gas, at the end of expiration. From the appearance of the temperature tracings, the thermocouple was judged to respond fast enough to give a true reading.

**Compressed gas in the tubing** may cause an overestimate in $V_{\text{CO}_2}$, since the compressed gas is released though the flow meter without passing the cuvette. The overestimate of $V_{\text{CO}_2}$ at a particular instant is proportional to the concentration of carbon dioxide inside the cuvette. Tracings of $FE_{\text{CO}_2}$ and airway pressure from 10 patients with healthy lungs, in whom an endotracheal tube had been passed, were recorded on paper at high speed in order to determine the effect of this artefact on the calculation of $V_{\text{CO}_2}$. The volume of compressed gas at the particular instant was regarded as being proportional to the pressure in the airway.

**Validation.** Mechanical ventilation of the lungs...
with air was used in 10 unconscious neurosurgical patients. The ventilator was equipped with a Bennett humidifier, and the tubing had a compliance of 19 ml kPa⁻¹. An original CO₂ Analyzer 930, without any modification to decrease its response time, was used. The expired gas was collected in a bag. Signals for $F_{E, CO₂}$ and $V_{E}$ from the carbon dioxide analyser were tape-recorded and later played back to a computer to obtain SBT-CO₂ tracings. PE$co_2$ was calculated from: $-F_{E, CO₂} = V_{T, CO₂}/V_T$, where $VT$ is tidal volume, $V_{T, CO₂}$ is equal to the area under the SBT-CO₂ tracing. This was compared with that obtained by direct measurement from the bag (Scholander, 1947). In addition, gas from the bag was passed through the carbon dioxide analyser as described by Fletcher (1980) and the digital value for $P_{TCO₂}$ noted.

**Analog calculation of $V_{T, CO₂}$.** The digital values for $V_{T, CO₂}$ presented on the CO₂ Analyzer 930 (which uses analog circuitry) were compared with those obtained by a digital computer, which presented the SBT-CO₂ tracings. One hundred and seventy-three observations were obtained at $V_{T, CO₂}$ values between 7 and 38 ml in 87 individuals.

**Results**

**Rebreathing of the gas in the tubing.** The way in which end-expiratory gas was cleared from both limbs of the Y-piece and adjacent tubing during inspiration is shown in figure 1. At a frequency of 10 b.p.m. the calculated rebreathed volume corresponded to 24 ml of end-expiratory gas. When the experiment was repeated with a Y-piece equipped with one-way valves, no rebreathing from the limbs of the Y-piece or tubing could be observed.

**Effects of other gases.** The response of the carbon dioxide analyser was uniformly zero, whether 100% nitrous oxide, 100% oxygen, 100% nitrogen, or moist air at a temperature of about 37°C was introduced inside the cuvette.

Fletcher (1980) measured the effects of intermolecular interaction between carbon dioxide and the carrier gas. He found that the signal voltage, at a given $F_{CO₂}$, was about 20% greater with nitrous oxide as carrier gas, than with oxygen:

$$\text{Error} (%) \text{ in } F_{CO₂} = -5.80 + 0.223 \times (\% N₂O \text{ in } O₂)$$

$n = 46$, residual standard deviation (RSD) = 2.28, $r = 0.97$.

**Analyser delay.** Early models of the analyser were supplied with an operational amplifier of insufficient output and this caused a delay in the response to carbon dioxide. However, with a more powerful amplifier the delay in carbon dioxide analysis is about 4 ms with a total 50% response time of 12 ms (Fletcher, 1980). Since the delay in the $V_E$ signal is also about 4 ms, the two signals are virtually synchronous, the effective difference in response time being about 8 ms. Using the less powerful amplifier with a 50% response time of 26 ms, the principal effect of this delay is on phase II of SBT-CO₂, the S-shaped upswing. This affects estimation of airway deadspace ($V_{Dw}$). This was investigated in 10 patients: $V_{Dw}$ was overestimated by $11 \pm 2$ and $13 \pm 4$ ml at small and large tidal volumes respectively (Fletcher, 1980). The error was greatest at high airway flows. When slow components are used, the above figures for $V_{Dw}$ will result in under-estimation of $V_{T, CO₂}$ by about 1–3%. There was no error in phase III $F_{E, CO₂}$.

**Alinearity of carbon dioxide analysis.** The relationship between measured carbon dioxide concentration and that of the test gas for carbon dioxide dispersed in nitrous oxide in oxygen is shown in figure 2. The results are presented standardized to show the correct value at 4% carbon dioxide, a typical calibration gas concentration. During moderate hyperventilation, phase III of SBT-CO₂ (the “alveolar plateau”) lies in the range 3.0–4.0 kPa (unpublished observations). This implies that the $F_{CO₂}$ of phase III will usually be overestimated by 0–3%, if the calibration gas contains 4% carbon dioxide. The overestimation of phase II will be greater, but of less practical importance since this phase contains only about 1.5 ml of carbon dioxide.
in patients with a tracheal tube in situ. If the calibrating gas contains 6% carbon dioxide the error in phase III will be 4–7%.

A linearity of $\dot{V}E$ measurement. Figure 3 depicts the relationship between expiratory flow as measured from the wet gas meter and that obtained from the test ventilator. Two ventilators are represented. The results are standardized to show the correct value at a flow of 0.5 litre s$^{-1}$. The test gas was 50% nitrous oxide in oxygen.

Results obtained with the piston pump showed that the expiratory flow meter was linear also with air, 100% oxygen and 100% nitrous oxide, and again, finally, with 50% nitrous oxide in oxygen. At a given flow, air gave nearly the same signal voltage as 50% nitrous oxide in oxygen, while oxygen gave a reading 6–8% more and nitrous oxide a reading 5–7% less.

Variations in temperature of expired gas (fig. 4). The expired gas cools continuously as it passes the tracheal tube and the tube connector (12 cm). The gas is warmed at the carbon dioxide cuvette: it cools as it passes the expiratory tube (125 cm) and is warmed again at the flow meter. Changing tidal volume between 0.5 litre at a respiratory rate of 20 b.p.m. and 1.0 litre at 10 b.p.m. had little effect on these temperatures. Figure 4 shows also the tensions of water vapour at various points in the tubing, assuming that the condensation of water is complete during the passage of gas through the system. Partially desaturated gas passes through the carbon dioxide cuvette. The partial pressure of carbon dioxide and other gases is thus increased by about 1.5–2%, implying that $FE_{CO_2}$ will be increased by a factor of about 1.015–1.02.

In a separate experiment, dry gas containing 4.4% carbon dioxide in oxygen was passed through the carbon dioxide cuvette at a rate of 4–5 litre min$^{-1}$, either after heating the gas to 36–40°C or keeping it at room temperature until it reached the cuvette. The reading of the carbon dioxide analyser did not differ. In yet another study, the ventilator was connected either to a patient or to a 4-litre rubber bag at room temperature. The temperature observed immediately distal to the expiratory flow meter was the same: about 33°C on both occasions. In a third experiment, gas returning from a ventilated bag was warmed by immersing the tubings in a water bath at 42.5°C. $\dot{V}E$ was exactly the same as when the gas was returned at room temperature.
**The effect of compressed gas in the tubings.** During expiration, most of the compressed volume leaves the tubing before carbon dioxide from the patient reaches the cuvette. However, at this point airway pressure is still increased, indicating that some compressed gas is still in the system. The fractions of compressed gas leaving during different phases of expiration are shown in table I.

The compliance of standard tubing at normal clinical pressures is $19 \text{ ml kPa}^{-1}$ with a Bennet humidifier in the circuit and $7 \text{ ml kPa}^{-1}$ without. One can thus estimate the error in the calculation of tidal carbon dioxide production. As an example, one may consider the case of small $V_T$, a compliance of $19 \text{ ml kPa}^{-1}$ and an end-inspiratory pressure of $1.5 \text{ kPa}$. Compressed volume is $1.5 \times 19 = 28.5 \text{ ml}$. Table I shows that $0.23$ of this (6.6 ml) will be released during phase III. This corresponds to an overestimate of tidal carbon dioxide elimination of $6.6 \times 0.04 = 0.26 \text{ ml}$, assuming that phase III $F'E_{CO_2}$ is 0.04. Without humidifier the error is 0.1 ml. Table I also shows that the overestimate caused by phase II can be neglected.

**Validation.** Figure 5 relates $F'E_{CO_2}$, as obtained by instantaneous calculation of carbon dioxide flow and its integration over time by the computer, to $F'E_{CO_2}$ from Scholander analysis of mixed expired gas during ventilation with air. Calibration of the expiratory flow meter and the carbon dioxide unit was performed before each experiment. Corrections were made in the figure for rebreathing, which was taken to be $24 \text{ ml}$ end-tidal gas per breath, and the effects on $V'T_{CO_2}$ of (a) variations in humidity, (b) compressed gas, and (c) analyser delay, as described above.

**Table I. Fraction of compressed volume discharged during various phases of expiration in 10 patients (mean ± 1 SD)**

<table>
<thead>
<tr>
<th>Fraction of compressed volume</th>
<th>Phase I (no CO$_2$)</th>
<th>Phase II (rapid increase in CO$_2$)</th>
<th>Phase III (&quot;alveolar plateau&quot;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small $V_T$</td>
<td>0.67 ± 0.06</td>
<td>0.10 ± 0.03</td>
<td>0.23 ± 0.05</td>
</tr>
<tr>
<td>Large $V_T$</td>
<td>0.62 ± 0.09</td>
<td>0.10 ± 0.03</td>
<td>0.29 ± 0.07</td>
</tr>
</tbody>
</table>

The regression equation between Scholander analysis ($x$) and $FE_{CO_2}$ (dry gas) by electronic integration ($y$) is:

$$y = -0.00217 + 1.093 \times x$$

**RSD = 0.0012, $r = 0.96$**

The intercept does not differ significantly from 0 ($P < 0.2$). There is no significant trend towards a systematic difference between the two techniques for assay when results obtained with fast and slow respiratory rates were pooled. However, the analyser overestimates $FE_{CO_2}$ slightly at slow rates (by 0.00034 ± 0.00034 (SEM), $n = 10$; where SEM = standard error of the mean) and underestimates it at fast rates (by 0.00044 ± 0.00041, $n = 9$). The difference between the errors at fast and slow rates was significant ($P < 0.05$).

When the gas from the sack was passed through the ventilator, there was good agreement between the two infra-red methods: $FE_{CO_2}$ by electronic integration underestimated the $FE_{CO_2}$ of the sack by 0.00062 ± 0.00045 ($n = 5$) and 0.00017 ± 0.00037 ($n = 6$) at fast and slow rates respectively.
FIG. 5. The relationship between $F_{\text{ECO}_2}$ obtained by electronic integration of instantaneous $F_{\text{ECO}_2}$ as measured by the carbon dioxide analyser to $F_{\text{ECO}_2}$ obtained by Scholander analysis in nine patients. All values are for dry gas.) Measurements were made both at large tidal volume and respiratory rate 10 b.p.m. (●), and at small tidal volume with respiratory rate 20 b.p.m. (○). Corrections for various sources of error are made, as described in the text. Pairs of readings are joined by lines. The line of identity is shown.

**Analog calculation of $V_{\text{T CO}_2}$**. The relationship between $V_{\text{T CO}_2}$ by analogue calculation ($y$) and digital calculation ($x$) is

$$y = -0.2 + 1.00 \times x$$

RSD = 1.0, $r = 0.99$

The intercept does not differ significantly from zero ($P > 0.2$).

**DISCUSSION**

The CO$_2$ Analyzer 930 calculates carbon dioxide elimination from instantaneous measurement of $V_E$ and $F_{\text{ECO}_2}$. The principle may also be applied to measurement of the elimination of other gases, such as oxygen, and tracer gases used in the investigation of lung function. An account of methodological errors is therefore of wider interest.

The importance of the various sources of error in carbon dioxide analysis is summarized in table II. It can be seen that it is possible to eliminate one of these by choosing low compliance tubing. Further accuracy can be gained by using an analyser with fast components, although even "slow" components give a response which is rapid compared with other analyser systems (26 ms 50% response time). The effects of barometric pressure (Olsson et al., 1980) and changes in temperature during expiration are easily compensated for.

In clinical practice, we have found that the calibration is stable for several months. However, it should be borne in mind that a 1-kPa increase in atmospheric pressure will give a 1.8% increase in the
TABLE II. Importance of various sources of error

<table>
<thead>
<tr>
<th>Source of error</th>
<th>Effect on measured $FE_{CO_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rebreathing</td>
<td>Overestimation by 5–12% when $f$ varies between 10 and 20 b.p.m. in the slightly hyperventilated adult ($P_{E,CO_2} = 4.5 \text{kPa}$). Greater in the hypoventilated patient.</td>
</tr>
<tr>
<td>Effects of other gases</td>
<td>Reading 20% greater with nitrous oxide as carrier gas, than with oxygen.</td>
</tr>
<tr>
<td>Delay in CO$_2$ analysis</td>
<td>Negligible with a fast amplifier. Underestimation by 2% with a slow amplifier.</td>
</tr>
<tr>
<td>Alinearity of CO$_2$ analysis</td>
<td>None with CO$_2$ in air. Overestimation by 0–3% with CO$_2$ in N$_2$O:O$<em>2$, depending on $FE</em>{CO_2}$ and with suitable calibration gas.</td>
</tr>
<tr>
<td>Alinearity of $VE$</td>
<td>None.</td>
</tr>
<tr>
<td>Variations in temperature and water content of expired gas.</td>
<td>Overestimation by 1–2%.</td>
</tr>
<tr>
<td>Compressed gas in the tubings</td>
<td>Negligible in the adult when compliance of the tubing is less than 10 ml kPa$^{-1}$. Overestimation by 2.5% at $f = 20$ b.p.m. and a compliance of 20 ml kPa$^{-1}$. About 1% overestimate at $f = 10$ b.p.m.</td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>Increases by 1.8% when barometric pressure increased by 1 kPa.</td>
</tr>
</tbody>
</table>

$FE_{CO_2}$ signal. Therefore, for some scientific work it may be desirable to calibrate daily. Pressure variations in the cuvette during the respiratory cycle are of little consequence. Except at very high expiratory flows, airway pressure will be less than 0.5 kPa when carbon dioxide is present in the cuvette.

Under the above circumstances, only rebreathing remains as an important source of uncertainty in the measurement. Previously it has been shown that the carbon dioxide analysis is linear in air (Olsson et al., 1980). With nitrous oxide in oxygen ventilation, a small correction for alinearity of the carbon dioxide analyser may be required, depending on the calibration gas used. The error will be least if the $FCO_2$ of the calibration gas is the same as that typically found during phase III of SBT-CO$_2$, that is 0.03–0.04. It should be noted that, even for clinical use, allowance must be made for the effects of intermolecular interaction between carbon dioxide and the carrier gas, as the reading is about 20% greater with nitrous oxide than with oxygen.

The linearity of the expiratory flow meter has been a matter of concern to some investigators. Although the results shown here are completely satisfactory, it must be remembered that accurate flow measurement demands that the resistance net of the flow meter is kept in good condition. This requirement necessitates placing the flow meter in the ventilator. If placed at the Y-piece, next to the carbon dioxide sensor, mucus deposited on the net from the patient’s airway would affect measurement of $VE$. The arrival of foreign material in the carbon dioxide sensor only affects $FCO_2$ measurement for one breath (Olsson et al., 1980). As discussed above, errors may arise when the flow meter and sensor are placed at different sites; however, we have shown that these errors are small if the compliance of the tubing is low. We believe that the reliability of flow measurement achieved with the present system outweighs the possible advantages to be gained by measuring $VE$ at the Y-piece.

The validation experiments show that it is possible to obtain accurate values for $FE_{CO_2}$ if the corrections, outlined above, are made. The trend towards overestimation of $FE_{CO_2}$ at slow respiratory rates and underestimation at fast rates can probably be explained as follows. With low frequency, large tidal volume ventilation, expiratory flow rates and expiratory time are greater, allowing more mixing and diffusion of expiratory gas in the inspiratory limb of the Y-piece. In practice, it is difficult to know exactly the rebreathed volume with different ventilatory patterns. The present results suggest that the variation, although statistically significant in our example, is so small that it can be neglected under most conditions prevailing during ventilation of adults. Possibly, the simplest solution to the problem is to avoid rebreathing by the use of non-return valves in the Y-piece.

The effect of rebreathing is greatest at high ventilator frequencies, as during ventilation of the lungs in infants. The error in this case can be minimized by using the special paediatric Y-piece and tubing. With low frequency, large tidal volume mechanical ventilation in adults, rebreathing has minimal effects.

Equation (3) shows that there is no systematic
error in the analog calculation of $V_T \cdot CO_2$, as compared with computer calculation. The spread of values about the regression line (SD = 1.0 ml) can be explained by the difficulty in knowing exactly which breaths have been analysed by the computer. A breath-to-breath variation in $V_T \cdot CO_2$ of 1 ml is common in our experience.

Finally, a point about the conversion of measured expired volume to BTPS should be noted. Figure 4 shows that expired gas from the patient is cooled to within a few degrees of room temperature, and is then heated at the flow meter to $33-34 ^\circ C$. The latter is the same temperature as is reached when a rubber bag is ventilated, for example during calibration of the flow meter against a dry or wet gas meter. We conclude from this that the temperature of the gas, when passing the flow meter, is about the same in both instances. In other words, a flow of a certain number of moles per minute of a gas will give the same reading whether or not the gas has been preheated in a patient, before passing the flow meter. If the calibration of the flow meter is carried out at a room temperature of $20 ^\circ C$ then a factor of $(273 + 37)/(273 + 20) = 1.06$ should be applied in order to convert expired volume to BTP. Expired gas from the patient cools in the tubing, to a minimum temperature of about $26 ^\circ C$ (fig. 4), corresponding to a vapour pressure of 3.4 kPa. The correction factor, for condensation of water vapour, is therefore $(100 - 3.4)/(100 - 6.4) = 1.03$. The total conversion factor to BTPS, of measured expired volume, is thus $1.03 \times 1.06 = 1.09$.

REFERENCES

ZUSAMMENFASSUNG

CAUSAS DE ERROR Y SU CORRECCIÓN EN LA MEDICIÓN DE LA ELIMINACIÓN DE ANHÍDRIDO CARBÓNICO POR MEDIO DEL ANALIZADOR DE CO$_2$ DE SIEMENS–ELEMA

SUMARIO

El analizador de CO$_2$ 930 de Siemens–Elema permite el cálculo de la eliminación de anhidrido carbónico mediante la medición instantánea de la corriente de gas expirado ($V_E$) y de la fracción de anhidrido carbónico ($F_{\text{CO}_2}$). El $V_E$ se mide en el ventilador y la $P_{\text{CO}_2}$ en el elemento en Y. La causa más frecuente de los errores de medición de la eliminación del anhidrido carbónico la constituye la re-respiración que corresponde a 24 ml de gas exipiratorio-terminal aproximadamente por aliento con el elemento en Y estandar y el tubo. Puede reducirse el problema mediante el uso de válvulas sin retorno en el elemento en Y. Debe preverse una tolerancia respecto de los efectos de la interacción intermolecular entre el anhidrido carbónico y el gas transportador, puesto que la lectura con óxido nitroso sobrepasa en un 20% aproximadamente la que se obtiene con oxígeno. Puede evitarse ese problema y en grandes proporciones al usar la calibración de mezclas gaseosas apropiadas. Son pequeños los errores provenientes de la demora del analizador y pueden eliminarse totalmente por la inclusión de componentes electrónicos veloces. El análisis del anhidrido carbónico es lineal con el aire como gas transportador, pero ligeramente alinear con mezclas de óxido nitroso en oxígeno. Puede reducirse al mínimo dicho error al usar una calibración de gases con un tenor de anhidrido carbónico semejante al del gas expirado. Las variaciones de temperatura y de contenido de agua del gas expirado provocan una sobre-estimación de la fracción promedio de anhidrido carbónico expirado ($F_{\text{CO}_2}$) conforme a un factor del 1,01–1,02. El gas comprimido en el tubo causa un pequeño error despreciable en presiones normales de las vías respiratorias con tubos de baja elasticidad. La presión barométrica afecta ligeramente la medición del anhidrido carbónico. Durante la ventilación mecánica de los pulmones de 10 pacientes con aire, la $P_{\text{CO}_2}$ obtenida después de las correcciones debidas a los errores conocidos concordaban bien con el análisis de Scholander de los gases expirados mezclados.