Gas exchange measurement in module M-COVX

This document explains how the gas exchange measurement in the gas module M-COVX works.

1. Basic equations

To obtain the oxygen consumption $VO_2$ of a patient, one must measure the amount of oxygen that is inhaled and subtract from it the amount exhaled. These amounts can be obtained by multiplying each measured volume piece $dv$ by the corresponding gas concentration $f$:

$$VO_2 = \int_{i} f_{O_2} dv - \int_{e} f_{O_2} dv$$

CO2 production $VC_{O_2}$ is obtained similarly

$$VC_{O_2} = \int_{i} f_{CO_2} dv - \int_{e} f_{CO_2} dv$$

Using inspiratory and expiratory minute volumes $MV_i$ and $MV_e$ and volume-averaged inspiratory and expiratory concentrations $f_i$ and $f_e$, these equations can be written

$$VO_2 = f_i O_2 MV_i - f_e O_2 MV_e$$
$$VC_{O_2} = f_e CO_2 MV_e - f_i CO_2 MV_i$$

To make the results less sensitive to errors in volume measurements, the well-known Haldane transformation can be applied. This means taking advantage of the fact that the patient is not consuming nor producing nitrogen, so that the amount of nitrogen inhaled is equal to the amount exhaled:

$$f_i N_2 MV_i = f_e N_2 MV_e.$$ 

$VO_2$ and $VC_{O_2}$ can then be written using either inspiratory minute volume:

$$VO_2 = (f_i O_2 - f_{Hald} f_e O_2) MV_i$$
$$VC_{O_2} = (f_{Hald} f_e CO_2 - f_i CO_2) MV_i$$

or expiratory minute volume:

$$VO_2 = (f_i O_2/f_{Hald} - f_e O_2) MV_e$$
$$VC_{O_2} = (f_e CO_2 - f_i CO_2/f_{Hald}) MV_e$$

where

$$f_{Hald} = f_i N_2/f_e N_2 = (1 - f_i O_2 - f_i CO_2)/(1 - f_e O_2 - f_e CO_2).$$

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M-COVX measures inspiratory volumes more accurately than expiratory volumes, and therefore the former equations with \( MV_i \) are applied. At \( \text{FiO}_2 \) levels higher than 65%, however, \( VCO_2 \) is approximated by

\[
VCO_2 = (f\text{eCO}_2 - f\text{iCO}_2) MV_e.
\]

Deltatrac measures only expiratory minute volume and uses the \( MV_e \)-based formulation.

2. Synchronization of gas and volume data

The measurements of gas concentration and airway flow/volume are not performed simultaneously. When a gas sample is passing through the Dlite, the flow at that moment is obtained almost instantly as the pressure difference travels via the spirometry tubings with the speed of sound. In contrast, it takes about 1.1 s for the gas sample to travel through the sampling system to the \( \text{CO}_2 \) sensor, and about 0.6 s more to reach the \( \text{O}_2 \) sensor. These delay times are continuously measured and compensated for in order to obtain the volume-averaged inspiratory and expiratory gas concentrations.

Figures 1 - 2 describe the measurement schematically. A sampling connector (1) for a gas analyzer and a spirometer is located between the Y-piece (2) of the ventilatory circuit and the intubation tube (3). A gas sample is continuously sucked via the sampling tube (4) from the connector to the gas analyzer unit (5) of the measuring device. Pressures on both sides of a flow restriction (6) are communicated via the spirometer tubes (7) to the spirometer unit (8) of the device.
Upper part of Figure 2 is a schematical picture of the gas analyzing unit (5). CO2 concentration is measured by an infrared absorption sensor (9), and O2 concentration is measured by a paramagnetic resonance sensor (10). The rise times of these measurements are compensated for by deconvolution procedures.

When the gas sample enters the device, moisture is removed in the water separator (11). The flow is divided into two parts, one of which goes through the gas sensors (9) and (10) and to the bypass flow (12). The reference gas (13) required for the paramagnetic measurement is taken from room air. When the zero valve (14) is closed, input flow is taken from room air for a readjustment of the zero levels of the gas concentration measurements. If an occlusion takes place in the sampling tubes, the occlusion valve (15) is closed and sample flow will completely bypass the analyzers. The power of the pump (16) is then effectively employed in an effort to clear the occlusion.

Sample flow $v_s$ is measured by the pressure transducer (17) which senses the pressure difference $\Delta p_s$ over a flow restrictor between the CO2 and O2 sensors.

Lower part of Figure 2 shows the spirometer unit (8) of the device. Pressures communicated via the spirometry tubes are converted to an airway pressure signal $p_{aw}$ (19) and an airway pressure difference signal $\Delta p_{aw}$ (20). Airway flow $v_{aw}$ is computed from $p_{aw}$. 
2.1. Corrected sample flow measurement

2.2. Compensation of pressure variations

2.3. Reducing sample flow variations

2.4. Compensation of variations in sample line volume $V_s$

2.4.1. Measurement of $V_s$

2.4.2 Adjustment of $V_s$

2.5. Integration of gas concentration samples

3. Deformation of gas concentration curves

The gas curves as we see them on the monitor screen do not look the same as they would had they been measured at Dlite by an imaginary infinitely fast device. First, some mixing of gas which softens the front regions between inspiratory and expiratory gases has taken place during the transport of the gas via the sampling system. Second, the CO2 and O2 sensors are not infinitely fast but have a finite measurement rise time, largely due to the fact that they measure a finite volume of gas. A set of transformations is performed that
reduces the measured gas signal back to the concentration pattern at the sampling point of the Dlite at the time instant when the sample is taken.

3.1. Rise time

3.2. Mixing

4. Accuracy of VO2 and VCO2 in the M-COVX module

According to the laboratory measurements and clinical tests, the method gives VO2 and VCO2 within +/- 10% accuracy up to fiO2 < 65% and within +/- 15% accuracy for 65% < fiO2 < 85%. Some further restrictions for applying the method have been found:

• respiration rate RR < 35/min
• inspiratory time Ti > 1 s if pressure swings are very high (ppeak - ppeep > 25 cmH2O)
• stable (mixed) fiO2 level
• less accurate in BIPAP mode

It is concluded that the method can be applied with sufficient accuracy in the majority of clinical situations; cases which meet the restrictions above are relatively rare.

5. Comparison to Deltatrac performance

The overall accuracy of the M-COVX method is less good than that of Deltatrac, which gives VO2 and VCO2 within +/- 6% accuracy for fiO2 < 65%. For Deltatrac high respiration rates or very short inspiratory times are not difficult, whereas Deltatrac also encounters problems for unstable fiO2 levels and in the BIPAP mode. The main factor in favor of M-COVX is its supreme ease of use. However, in certain situations M-COVX also possesses technical advantages over Deltatrac:

1. M-COVX adjusts to changes in gas concentration levels much faster. This was demonstrated in the laboratory in the following way: Both VO2 and VCO2 were kept constant, while the fiO2 level was switched from room air level to 40%. It took 13 minutes before Deltatrac again showed values with less than +/- 10% error; for M-COVX this took only 2 minutes which corresponds to the time that is needed for the respiratory system to reach a new dynamic equilibrium state. The reason for slow recovery of Deltatrac is that it takes time to clear the mixing chamber from “old” gas: some of it is left in the corners of the chamber affecting the measurement for a longer time than the absolute volume/flow ratio would suggest.

2. For low respiration rates Deltatrac shows higher standard deviations of VO2 and VCO2 values than M-COVX does. At respiration rate of 6/min, successive minute values may in a stable state differ by 20%. The reason is that Deltatrac has no means to find out when a breath starts or ends. Certain minute value may in the worst case consist of, say, seven inspirations but only six expirations, while the next minute then includes six inspirations and seven expirations. M-COVX shows balanced values of complete breaths, so low respiration rates are not a problem.

3. At low diluted CO2 levels Deltatrac is unable to measure accurately. If the metabolic rate of a patient is very low, CO2 concentration in the mixing chamber of Deltatrac may be too low for accurate measurements. The problem can be solved by switching Deltatrac to the child mode. This is, however, only possible if the minute volume is below the maximum limit specified for this mode. These situations do not pose any problem for M-COVX as no dilution is performed.

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