

Appliguide

PDF PROOF

**Gas exchange and
indirect calorimetry**



PDF PROOF

Datex®, Ohmeda® and other trademarks are property of Instrumentarium Corp. or its subsidiaries. All other product and company names are property of their respective owners.

Clinical Application Guide of Gas exchange and indirect calorimetry

Jukka Takala, MD, PhD
Professor of Anesthesiology and Intensive Care
Director, Critical Care Research Program
Division of Intensive Care
Department of Anesthesiology and Intensive Care
Kuopio University Hospital
Kuopio, Finland

Correspondence:

Jukka Takala
Department of Anesthesiology and Intensive Care
Kuopio University Hospital
FIN-70210 Kuopio, Finland
Tel +358 17 173 311
Fax +358 17 173 443
e-mail: jukka.takala@kuh.fi

Table of Contents

Foreward	1
Introduction	2
Methodological considerations of gas exchange measurements	3
Deltatrac	3
Bedside module	6
Physiological aspects of gas exchange measurements	9
Oxygen consumption	9
Carbon dioxide production	10
Respiratory quotient and respiratory exchange ratio	11
Energy expenditure	12
Methodological considerations of clinical applications	13
Representative examples and case studies of the clinical application of gas exchange measurements	15
Preoperative nutritional support	15
Prolonged postoperative nutritional support	17
Prolonged intensive care	18
Nutrition and ventilation	21
Changes in oxygen consumption and oxygen delivery	23
Continuous monitoring of cardiac output	24
Components of ventilatory demand	25
Increase in ventilatory demand	26
Measurement of alveolar ventilation	27
Technical problems and physiological changes	28
Summary	32
Suggested reading	33

Foreward

The purpose of this book is to give an introduction to the basic principles and clinical applications of gas exchange measurements. The physiological and technical background is discussed briefly and the focus is on demonstrative examples on the clinical applications.

For those interested in more advanced and detailed physiological and technical information, references are made to the “Handbook of Gas Exchange and Indirect Calorimetry” (J. Takala and P. Meriläinen, Datex-Ohmeda Document 876710).

PDF PROOF

Introduction

Recent advancements in medical technology have made possible accurate measurement of respiratory gas exchange in a wide variety of clinical conditions. The modern indirect calorimetry devices are portable and easy to use, which facilitates routine clinical measurements. The clinical applications range from assessment of energy requirements and response to nutrition in malnutrition and obesity to comprehensive analysis of ventilation and oxygen transport in patients with complex cardiorespiratory problems. Though the measurements can be made easily, accuracy and reproducibility of results requires understanding of the basic principles of the measurement and related physiology. Furthermore, indirect calorimetry is sensitive to measurement errors; the need for routine procedures of quality control is therefore emphasized.

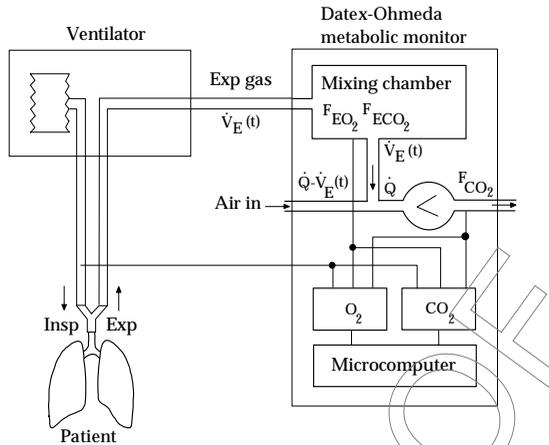
Despite accurate measurement, several clinical and physiological factors influence the results of gas exchange measurements and should be considered in interpretation. In this respect, the relationship between ventilation and gas exchange is of crucial importance. Any acute change in alveolar ventilation will be immediately reflected in CO_2 -production, which will not measure the metabolic production of CO_2 , until a new steady-state has been achieved. Similar, but shorter transient will be seen also in O_2 -consumption. Analogously, acute changes in tissue perfusion may influence both tissue oxygen uptake and removal of CO_2 from the tissues. These issues will be discussed in more detail in “Physiological aspects of gas exchange measurements”.

Methodological considerations of gas exchange measurements

Modern equipment for indirect calorimetry makes continuous, non-invasive monitoring of respiratory gas exchange possible. Most current devices apply the open circuit technique, where the expired gases are collected, the volume or flow of gas measured, and the inspiratory and expiratory concentrations of oxygen and carbon dioxide analyzed. Oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) are calculated from this data. Both the inspiratory and expiratory flow must be measured, or, more commonly, one of the flows measured and the other estimated using the Haldane transformation. The Haldane transformation assumes that only O_2 and CO_2 are exchanged in the lungs and the rest of the respiratory gases (excluding water vapor) have the same volume in both inspiratory and expiratory gases. When one of the flows is known, the other can be calculated. Measurement of respiratory gas flow continuously is associated with several problems, such as the effects of humidity, alternating gas composition, secretions, and the dynamic response of the flow sensors. Complicated compensation and calibration algorithms, and frequent cleaning are required to eliminate these effects.

Deltatrac

The Deltatrac avoids the problems of flow sensors by using a dilution method, where the expiratory gases are diluted in a known, constant flow.



$$\dot{V}_{CO_2} = \dot{Q} \cdot F_{CO_2}$$

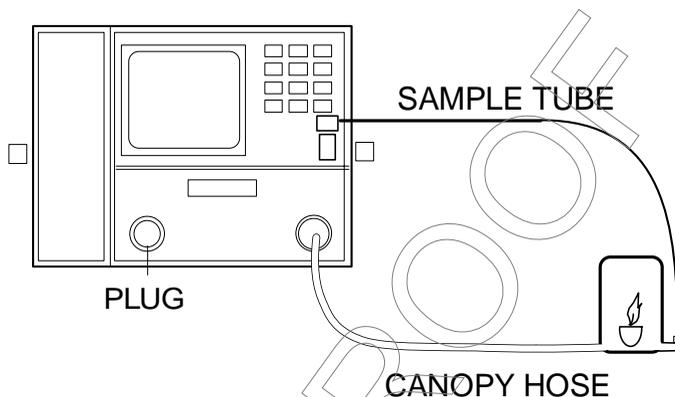
$$RQ = \frac{1 - F_{IO_2}}{F_{IO_2} - F_{EO_2} - \frac{F_{ECO_2}}{F_{CO_2}} \cdot F_{IO_2}}$$

$$\dot{V}_{O_2} = \dot{V}_{CO_2} / RQ$$

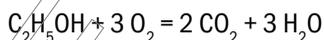
The constant flow generator keeps the output flow of the system fixed and independent of the amount of the added expiratory gases. Multiplexed sampling of the inspired, expired, and diluted expired gases is required and the Haldane transformation is applied. The details of the measurement technique are explained in the “Handbook of Gas Exchange and Indirect Calorimetry”, pgs 39-41.

The ease of use of the modern gas exchange monitors may sometimes create unfounded confidence in the user. Need for rigorous calibration of gas sensors, flow, and the overall system performance is the inherent characteristic of any method for indirect calorimetry. The key component of the method utilized by the Deltatrac is the constant flow generator. Its stability over a long time is apparently good, but its performance should nevertheless be checked regularly. The alcohol burning kit provided by the

manufacturer offers an easy and reproducible way for quantitative burning of alcohol. When a known amount of alcohol is burned and the total amount of CO₂ produced measured and compared to the predicted amount of CO₂, the flow of the constant flow generator can be calculated.



Ethanol is oxidized according to the following chemical reaction:



The atomic weight of carbon, hydrogen and oxygen, as well as the calculated molecular weight of ethanol are given in the following table.

C	12.011 g
H	1.008 g
O	15.999 g
C ₂ H ₅ OH	46.069 g

The molar volume of gases in STPD (Standard Temperature and Pressure, Dry gas) conditions is 22.4138 l. Using the chemical reaction written above it is possible to calculate that 1 gram of ethanol will produce 0.973 liters of CO₂. The density is 0.78522 g/ml at 25°C. A dose of 5 ml of pure (100 %) ethanol will produce 3820 ml of CO₂.

Adult flow constant:

$$\text{New flow} = 1.03 * \frac{3820 \text{ ml}}{\text{total CO}_2 \text{ in ml}} * \text{old flow}$$

Pediatric flow constant:

$$\text{New flow} = \frac{3820 \text{ ml}}{\text{total CO}_2 \text{ in ml}} * \text{old flow}$$

The gas sensors should be calibrated before each measurement and the overall performance of the system checked regularly by measuring the RQ of burning alcohol. A detailed discussion on various aspects of the validity of gas exchange measurements can be found in the “Handbook of Gas Exchange and Indirect Calorimetry”, pgs 46-55.

Bedside module

Combined measurement of airway gases and flow enables continuous monitoring of oxygen consumption and carbon dioxide production with intubated patients. Energy expenditure and respiratory quotient can then also be calculated.

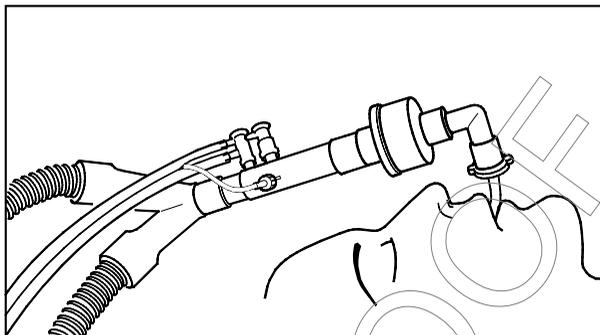
Inside the gas module the Datex-Ohmeda paramagnetic sensor is used to measure the O₂ curve and the infrared bench for the CO₂ curve. Both measurements are based on the side-stream principle.

In the D-lite flow sensor located at the patient’s airway the flow measurement is based on the pressure drop across a special proprietary turbulent flow restrictor.

Breath-by-breath measurement of pulmonary gas exchange is technically very demanding and requires sophisticated

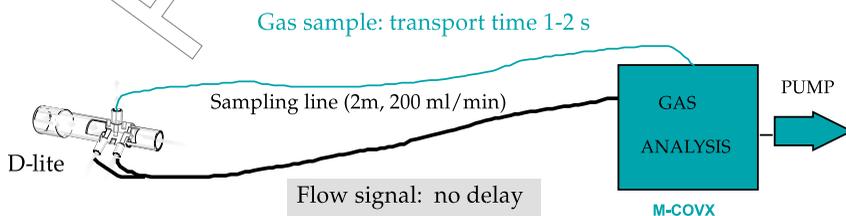
compensation and data processing algorithms to achieve the accuracy required in the clinical use.

FIGURE 1



Because of the side-stream principle the measurements of gas concentrations and flow are not simultaneous. When a gas sample passes through the D-lite, the flow signal is recorded with a negligible delay (less than 10 ms) since the pressure difference propagates to the module through the spirometry tubing with the speed of sound. In contrast, it takes in the order of 1.5s for the gas sample to travel through the sampling line to the module where first its O_2 and then CO_2 concentration are measured.

FIGURE 2

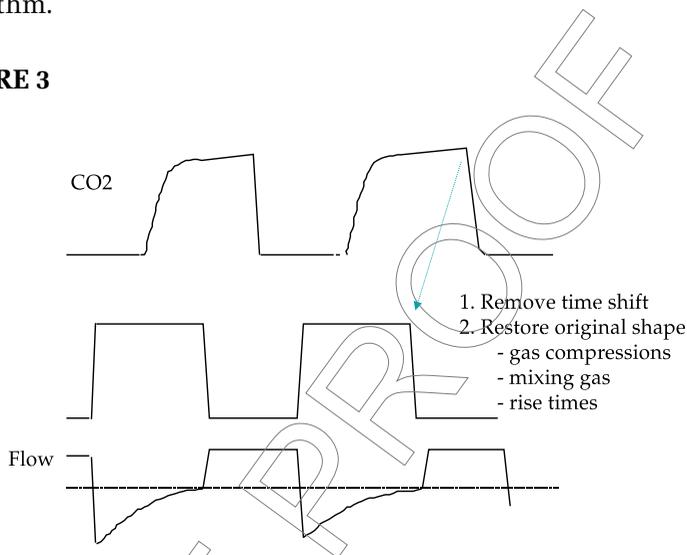


Synchronisation of gas and flow curves

The transport time delay is not constant, but must be compensated for the fluctuations in the sample flow, variations in the pressure at the D-lite and changes of the gas concentration.

In addition to these also the finite rise times of the O_2 and the CO_2 sensors need to be compensated utilizing a de-convolution algorithm.

FIGURE 3



Gas curve reconstruction

After reconstructing the original waveforms of the gas concentrations and shifting the curves to match the flow signal, the final calculations are based on an mathematical integration operation of the product of the flow and each gas signal. Additionally the Haldane transform is applied like in the Deltatrac to avoid need of absolute accuracy of the volume measurement in both flow directions. Since all these tasks require lot of parallel fast speed computing power dedicated algorithms have been developed to streamline the software to make it run in the module environment of limited processing capability.

Physiological aspects of gas exchange measurements

Gas exchange can be measured over a short period of time, even breath by breath with special equipment, but a period of at least 20 - 30 minutes is preferable. Prolonging the measurement period will give more valid information on the average gas exchange. Rapid, transient variations in gas exchange may be physiological, e.g. when caused by altered physical activity or state of alertness, or artefacts, e.g. if the inspiratory gas concentrations are unstable or a change in the breathing pattern (either during mechanical ventilation or spontaneous breathing) induces an abrupt change in the inspiratory or expiratory gas concentrations.

Oxygen consumption

Indirect calorimetry measures oxygen consumption as the uptake of oxygen from the respiratory gases. Acute changes in ventilation, hemodynamics, and physical activity may induce wide variations in the $\dot{V}O_2$ measured by any method. Since $\dot{V}O_2$ can be measured continuously, the transient changes in the measured $\dot{V}O_2$ can be readily observed in prolonged measurements.

Under aerobic conditions, $\dot{V}O_2$ depends on the metabolic activity of the tissues. At a given metabolic rate, the substrates of energy metabolism also have an impact on the $\dot{V}O_2$, since the amount of oxygen required to produce the same amount of energy from different substrates varies. The amount of oxygen needed to produce 1 kcal of energy from carbohydrate is 207 ml, from fat 213 ml, and from protein 223 ml.

If the amount of oxygen delivered to the tissues is inadequate for metabolic needs, tissue oxygen consumption becomes dependent on oxygen delivery and anaerobic metabolism with lactic acid production will ensue. During anaerobic metabolism, the $\dot{V}O_2$ measured from the respiratory gases does not reflect the tissue

oxygen needs, since an oxygen debt develops in the tissues. When aerobic conditions are restored, the oxygen debt will be reflected as increased oxygen consumption.

Carbon dioxide production

Measurement of carbon dioxide production ($\dot{V}CO_2$) by indirect calorimetry is susceptible to major errors unless the close relationship between $\dot{V}CO_2$, alveolar ventilation (VA), and arterial CO_2 ($PaCO_2$) is taken into account. According to the classical Bohr's equation, $\dot{V}CO_2 = \dot{V}A \times PaCO_2/k$, where k is a constant that depends on the units and the conditions (pressure, temperature, humidity) of the measurement. When $\dot{V}CO_2$ is given in ml/min, standard temperature (0°C), and dry gas (STPD), VA is given in L/min, 37 °C, and fully saturated with water vapour (BTPS), and $PaCO_2$ in kPa, the constant is equal to .1150. The Bohr's equation demonstrates that the measurement of $\dot{V}CO_2$ is sensitive to changes in ventilation: any change in alveolar ventilation will be directly reflected in $\dot{V}CO_2$ until a new steady state of $PaCO_2$ has been achieved.

In steady state, $\dot{V}CO_2$ depends on the metabolic activity of the tissues and, similar to $\dot{V}O_2$, on the substrates of the energy metabolism. Production of 1 kcal of energy from carbohydrate produces 207 ml of CO_2 , from fat 151 ml, and from protein 181 ml. If any of the variables in the Bohr's equation changes, the body CO_2 -pool will change. Under these circumstances, enough time should be allowed for the body pool of CO_2 to stabilize, if the measured $\dot{V}CO_2$ should reflect the metabolic production of CO_2 . The time required for the stabilization varies widely and ranges from 30 to 120 minutes. Continuous measurement of gas exchange facilitates the verification of a steady state.

Respiratory quotient and respiratory exchange ratio

The ratio between $\dot{V}CO_2$ and $\dot{V}O_2$ is called the respiratory quotient (RQ), when measured in steady state conditions. In non-steady state conditions, the expression “respiratory exchange ratio” is more appropriate. Assuming steady state conditions, the RQ reflects the mixture of substrates utilized by the energy metabolism. The RQ of carbohydrate is 1, the RQ of fat 0.7 and the RQ of protein approximately 0.81. Detailed analysis of substrate oxidation requires measurement of urinary urea excretion for the assessment of protein oxidation and calculation of the non-protein RQ. For the clinical purpose, major shifts in substrate oxidation will be reflected in the total RQ, as measured directly from the respiratory gases. Increased glucose oxidation will be observed as an RQ approaching 1, whereas increased fat oxidation will result in an RQ approaching 0.7. A steady state RQ above 1 indicates fat synthesis and is a clinical rarity, associated with excessive carbohydrate feeding. Even in these conditions, the RQ rarely exceeds 1.3. A steady state RQ below 0.7 is also a rarity, but may occur during ketosis, if the ketone bodies are incompletely oxidized and excreted into the urine. RQ-values exceeding 1 and below 0.7 should be carefully examined for measurement errors and the lack of a steady state. The most common causes of unphysiological or erroneous RQ-values are changes in ventilation: hyperventilation will increase the RQ and hypoventilation decrease it, until a new steady state of body CO_2 -pool has been achieved. Analogously, the development of an oxygen debt will increase the RQ, whereas replenishment of an oxygen debt will reduce the RQ.

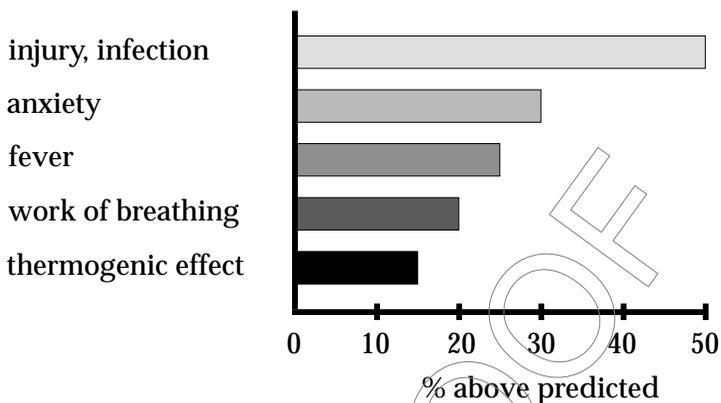
Energy expenditure

The energy expenditure cannot be directly measured by indirect calorimetry, but has to be calculated from the measured gas exchange variables and protein oxidation. The relative contribution of protein oxidation to the total energy expenditure is small even in catabolic conditions, and can be estimated or ignored without inducing a major error in the estimated energy expenditure. Several formulas are available for this purpose and the Weir formula is perhaps the most commonly utilized. When $\dot{V}O_2$ and $\dot{V}CO_2$ are given in ml/min STPD, and urinary urea nitrogen in g/day, energy expenditure in kcal/day = $5.50 \times \dot{V}O_2 + 1.76 \times \dot{V}CO_2 - 1.99 \times$ urinary urea nitrogen. For the mathematical basis of this formula, see "Handbook of Gas Exchange and Indirect Calorimetry", pg. 16.

Resting normal values for $\dot{V}O_2$ and $\dot{V}CO_2$ vary according to the body size, age, and sex of the patient. Rough estimates of normal values can be obtained by e.g. the Harris-Benedict formula, which is based on studies in healthy volunteers in 1919. Several studies have re-evaluated this formula, and indicated that it predicts the resting energy expenditure relatively accurately. For a more detailed discussion of the normal values, see "Handbook of Gas Exchange and Indirect Calorimetry", pgs 19-20.

An increase in energy expenditure will be reflected as a proportional increase in both $\dot{V}O_2$ and $\dot{V}CO_2$. Temporary increase of upto 200 % can occur due to e.g. shivering and convulsions. Clinical conditions associated with hypermetabolism, e.g. injury and sepsis, may increase the energy expenditure by upto 50 %, and in extreme cases upto 100 % (figure 4). Patients with severe pulmonary pathology and impairment of respiratory mechanics may have markedly increased work of breathing: the oxygen cost of breathing can be upto 20 % of whole body $\dot{V}O_2$, whereas it normally represents less than 5 % of the total $\dot{V}O_2$. Hemodynamic

FIGURE 4



Factors contributing to energy expenditure

catastrophies, such as a circulatory collapse, may acutely reduce both $\dot{V}O_2$ and $\dot{V}CO_2$, and a compensatory increase will be observed, once adequate tissue perfusion has been restored.

Methodological considerations of clinical applications

Measurement of gas exchange in the spontaneously breathing patient should preferably be performed with a canopy, since all methods interfering with the airway (e.g. mouthpieces and noseclips) alter the breathing pattern and may induce anxiety, which both modify the rates of $\dot{V}O_2$ and $\dot{V}CO_2$. When a canopy is used, large total flow through the canopy is needed to avoid CO_2 accumulation. The dilution of the expiratory gases to the large flow reduces the inspiratory-expiratory gas concentration differences, and use of increased inspiratory oxygen fraction in canopy measurements is therefore not possible with a standard canopy. However, a special supplementary oxygen canopy kit making the measurement feasible up to FIO_2 of 40 to 50 % has become available for the Deltatrac II.

Gas exchange measurement in the mechanically ventilated patient is prone to several potential sources of error:

- 1 High positive pressures in the ventilator patient circuit may influence the gas analyzers.
- 2 Haldane transformation cannot usually be used at high inspiratory fractions of oxygen. In practice, .60-.70 is the upper limit.
- 3 Instability of inspiratory oxygen fraction due to the characteristics of the gas blender and variation of the pressure of gases in the gas sources.
- 4 Leaks in the ventilator-patient circuit.
- 5 Temperature and humidity.

The errors related to the positive pressures and the effects of temperature and humidity can only be avoided by proper instrument design. Inspiratory oxygen concentrations can be stabilized by use of a mixing chamber (such as the humidifier) and a proper pressure regulator between the gas source and the ventilator (sufficient pressure and flow must be ascertained!).

The various techniques of ventilatory support may create both technical and physiological problems in the interpretation of the results. The variation of the inspiratory oxygen fraction is likely to be least during controlled mechanical ventilation, whereas more variation due to the technical characteristics of the gas blenders can be expected during other modes of ventilatory support, e.g. intermittent mandatory ventilation. In addition, a variable breathing pattern will inevitably increase the physiological variation of gas exchange. The effects of the physiological variation on the measured mean values can be minimized by prolonging the measurement.

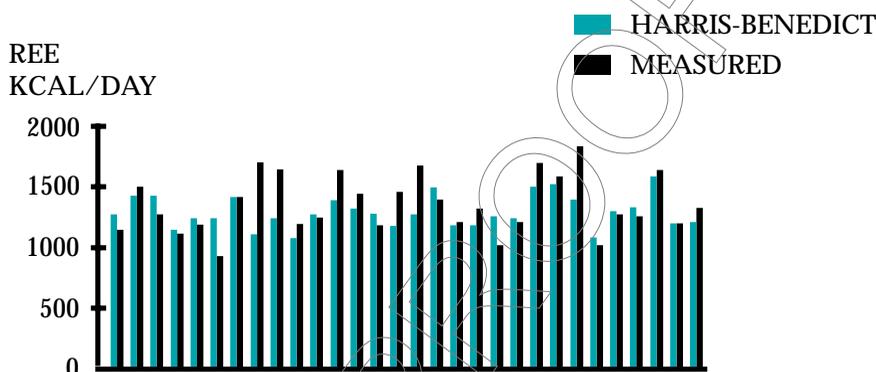
Representative examples and case studies of the clinical application of gas exchange measurements

Preoperative nutritional support

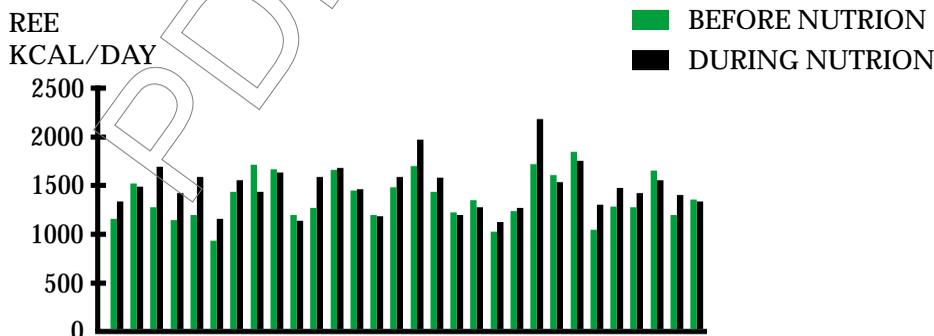
Figure 5-6: Preoperative nutritional repletion may be indicated in patients with significant recent weight loss and for whom major abdominal surgery is planned. The time available for the nutritional repletion is usually limited for practical reasons to approximately 1 - 2 weeks. The goal of adequate nutritional support is to start restoring the body composition, and therefore, both positive energy and nitrogen balance should be achieved. Many of the patients requiring preoperative nutritional support on clinical grounds suffer from malnutrition due to a malignant disease. While nutritional depletion per se tends to reduce the energy expenditure, the malignancy may substantially increase the energy expenditure, which makes the clinical evaluation of the energy needs difficult. Measurement of energy expenditure instead of estimation will assure that the preoperative nutritional support includes adequate amounts of energy without the risks of gross overfeeding. These figures demonstrate results from gas exchange measurements in 30 nutritionally depleted patients admitted for preoperative nutritional support before major gastrointestinal surgery. The variation of prenutrition energy expenditure is wide, and the difference between the measured and the predicted energy expenditure (calculated from the Harris-Benedict formula) cannot be predicted in individual patients (figure 2). In this case, approximately 1/3 of the patients appear markedly hypermetabolic despite nutritional depletion, and 1/6 are hypometabolic. The energy expenditure before nutritional support can be used as a guideline for nutritional requirements; however, marked changes may occur in energy expenditure as the result of nutrient administration. The response of energy expenditure to nutrition, containing approximately 1.2

times the measured prenutrition energy expenditure is shown in figures 2-3 for the same 30 patients. In approximately 1/6 of the patients, the increase in energy expenditure during nutrition is large enough to result in negative energy balance, unless the energy intake is increased further.

FIGURE 5

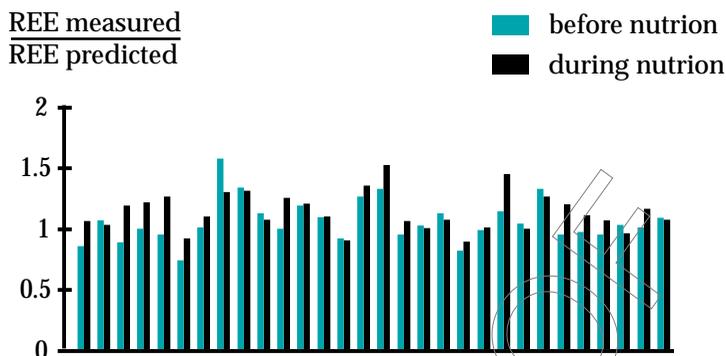


Predicted vs measured energy expenditure in depleted patients before preoperative nutrition support



Changes in energy expenditure during preoperative nutrition support in depleted patients

FIGURE 6



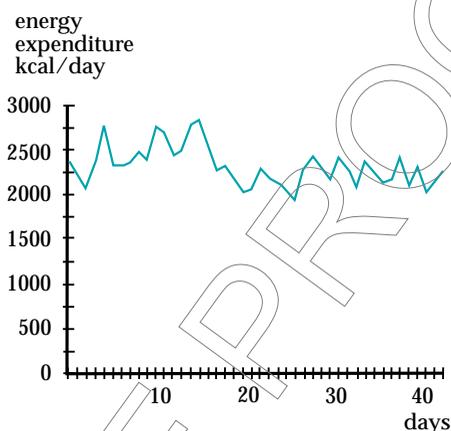
Changes in measured/predicted energy expenditure during preoperative nutrition support in depleted patients

Prolonged postoperative nutritional support

Figure 7: Postoperative complications after major gastrointestinal surgery may cause prolonged need for both parenteral and enteral nutritional support. Intercurrent infections, surgical interventions, and changes in the activity of the patient lead to wide variation in the energy expenditure and consequently, risk for inadequate nutrition is obvious. Prolonged negative energy balance may interfere with wound healing and rehabilitation, and overfeeding may increase the ventilatory demand during a period, when the patient's ventilatory function is compromised. This figure demonstrates the variation of energy expenditure in a patient, who underwent pancreatic resection after conservative management of acute pancreatitis. The postoperative course was complicated by severe acute respiratory failure and several septic episodes. The patient was grossly hypermetabolic for the first two weeks: his predicted energy expenditure was 1620 kcal/day and the actual energy expenditure ranged between 2100 and 2800 kcal (30 - 73 %

in excess of predicted). During recovery and gradual rehabilitation, he remained markedly hypermetabolic (approximately +30...+40 %) for several weeks. It is obvious that both the acute phase of a complicated, prolonged postoperative course and the phase of rehabilitation are associated with increased risk of nutritional depletion and measurement of energy expenditure will facilitate adequate nutritional support.

FIGURE 7



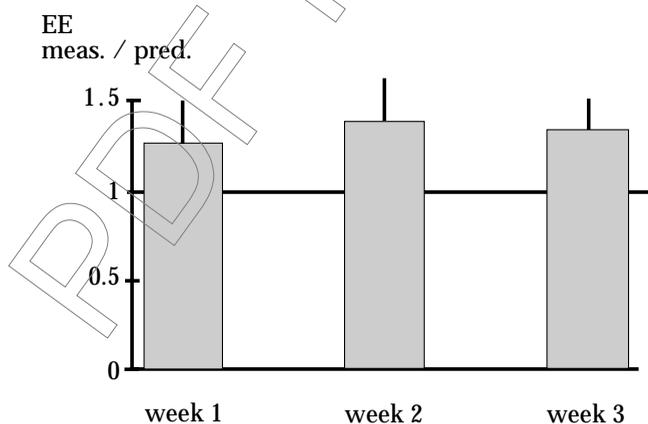
Energy expenditure during prolonged severe sepsis and gradual recovery

Prolonged intensive care

Figures 8-10: The average degree of hypermetabolism after surgery or injury in groups of patients can usually be predicted with relatively good accuracy. In patients with uncomplicated recovery, oral feeding can be reinstated rapidly and even gross errors in estimated energy needs are clinically irrelevant. Approximately 10 % of intensive care patients require prolonged intensive care. The average degree of hypermetabolism is relatively constant, as shown

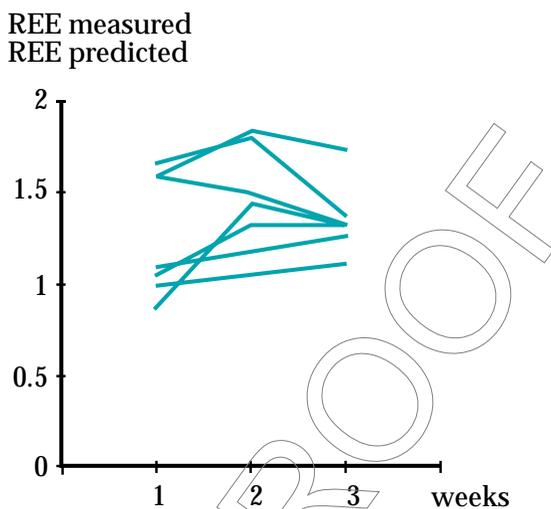
in figure 5 as the mean weekly energy expenditure (expressed as the ratio between measured and predicted energy expenditure) during three consecutive weeks for a group of 7 patients requiring prolonged intensive care. In contrast, the variation between individual patients (figure 9) as well as within a patient is extremely wide. Figure 10 demonstrates the pattern of daily energy expenditure for 30 consecutive days in a 28-years old male, who suffered severe III degree burn injuries in 50 % of the body surface area. As can be expected, the patient is hypermetabolic, but the degree of hypermetabolism varies widely, and is in general less than what could be expected from the traditional estimates. Since both gross overfeeding and prolonged negative energy balance should be avoided, measurement of energy expenditure markedly helps the design and maintenance of adequate nutrition in these patients.

FIGURE 8



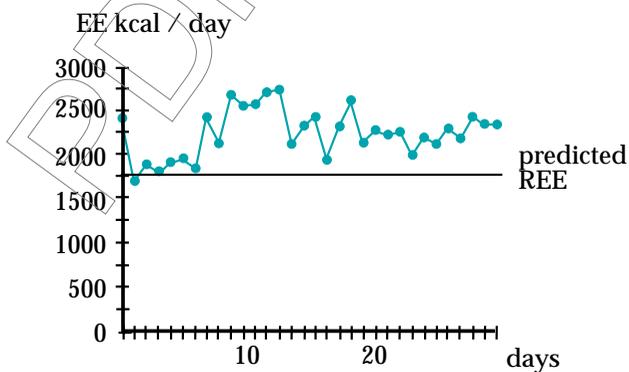
Hypermetabolism during prolonged intensive care

FIGURE 9



Variation of weekly mean energy expenditure during prolonged intensive care

FIGURE 10



Variation of energy expenditure during prolonged intensive care after major burn injury (50 % 3rd degree)

Nutrition and ventilation

The interrelations of energy metabolism, nutrition and ventilator dependency are schematically shown in figure 11. It is clear that muscular wasting as the result of malnutrition or hypercatabolism will inevitably also influence the performance of the respiratory muscles. Nutritional support may increase the ventilatory demand by increasing the CO_2 -production. CO_2 -production increases, if large amounts of carbohydrates are given with a consequent increase in RQ. Especially, if lipid synthesis is induced by overfeeding, the increase in CO_2 -production will be large. However, in patients with severely compromised ventilatory function, even relatively small shift in RQ can be critical in terms of the demand for minute ventilation. Figure 12 shows the changes in RQ, gas exchange and ventilatory demand in a patient with respiratory failure and prolonged ventilator dependency, where increasing the intake of lipids and the consequent reduction of RQ facilitated weaning. The measurement of gas exchange helped to maintain energy balance and make sure that the desired response to the nutritional manipulation was achieved. Since both overfeeding and malnutrition may cause weaning difficulties, measurement of gas exchange and energy expenditure is particularly useful in patients requiring prolonged mechanical ventilation.

FIGURE 11

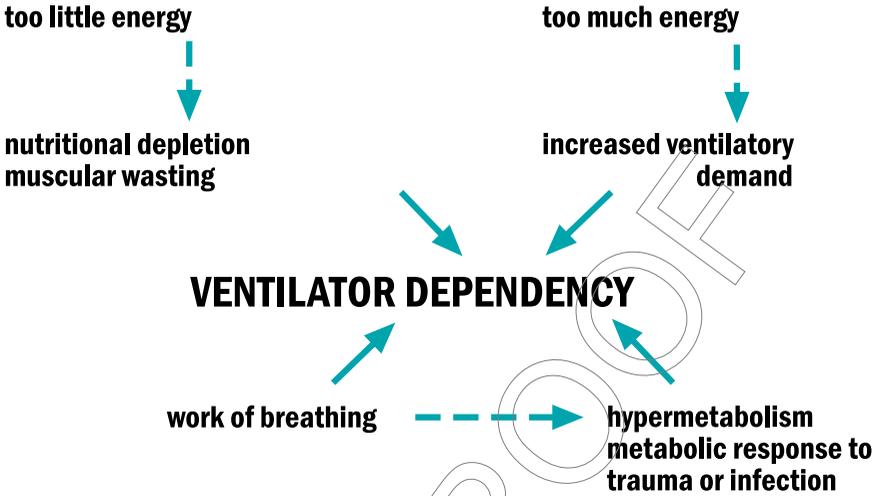
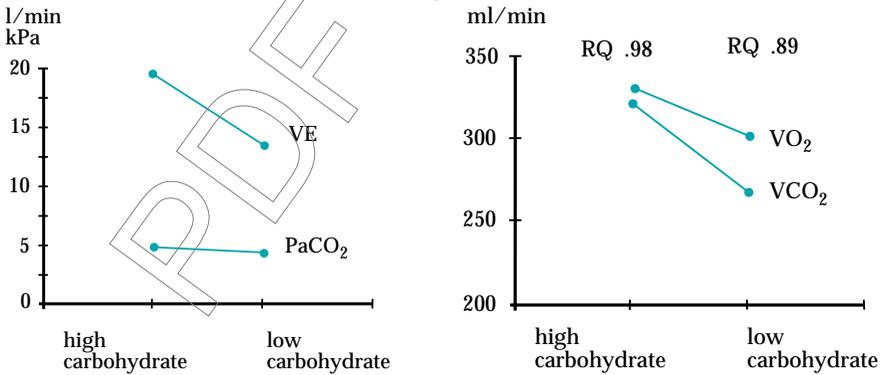


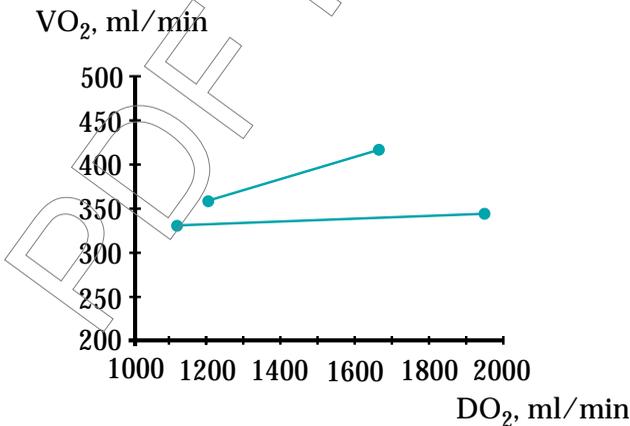
FIGURE 12



Changes in oxygen consumption and oxygen delivery

Simultaneous measurement of oxygen delivery and oxygen consumption can reveal signs of inadequate tissue perfusion. If oxygen consumption increases as a result of increased delivery, maintenance of the higher level of oxygen delivery may be beneficial. Figure 13 shows two patients with different patterns of responses of oxygen consumption to an acute increase of cardiac output (and oxygen delivery) in the adult respiratory distress syndrome. Inadequate tissue perfusion was suspected and a trial was made in which cardiac output was increased with dobutamine; the consequent marked increase in oxygen consumption in one of the patients was likely to reflect improved perfusion of tissues. On the other hand, when oxygen consumption increases, an increase in oxygen delivery is a normal physiologic response.

FIGURE 13



Response of VO_2 to acute increase in DO_2 in ARDS

Continuous monitoring of cardiac output

Figures 14-15: Cardiac output can be measured continuously by the Fick principle, when gas exchange data (oxygen consumption) is combined with arterial and mixed venous oxygen saturation data (available from oximeters) and haemoglobin. Relatively simple computer programs can continuously process the calculated cardiac output values. This facilitates monitoring of responses to vasoactive drugs and changes in ventilator management in patients with severely compromised cardiorespiratory function. These figures show the changes in cardiac output and oxygen delivery in a patient with a low cardiac output syndrome after open heart surgery and the response to treatment with vasoactive drugs and in a patient with severe ARDS during a trial PEEP. The failure to respond to dobutamine alone was rapidly evident and the prompt response to adding a vasodilator was observed. The level of PEEP resulting in maximum oxygen delivery could be rapidly detected during the application of PEEP in ARDS.

FIGURE 14

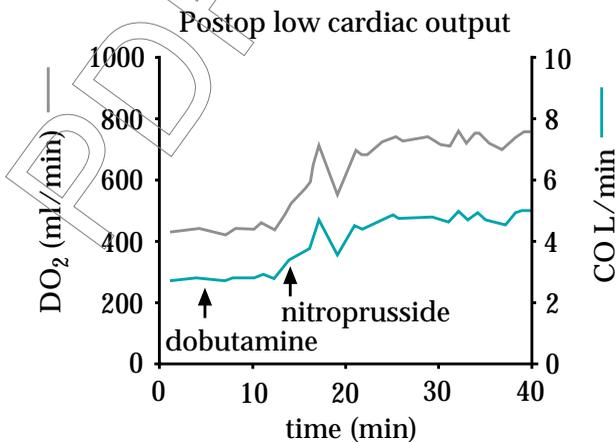
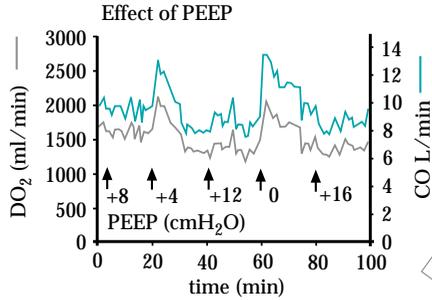


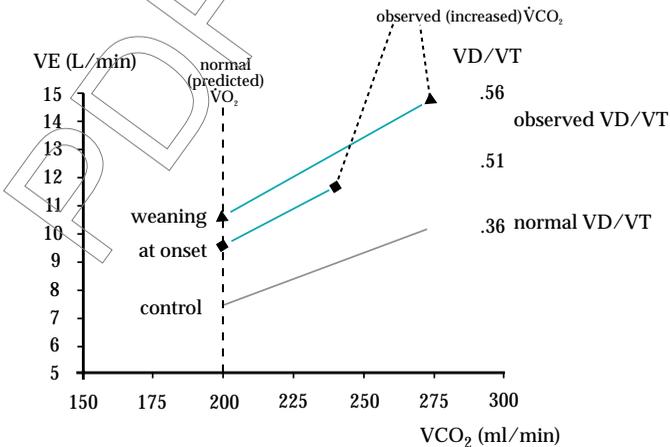
FIGURE 15



Components of ventilatory demand

Figure 16: Measurement of gas exchange can be used to evaluate the components of increased ventilatory demand, when the Bohr’s equation ($\dot{V}_E = .1150 \times \dot{V}\text{CO}_2 / \text{PaCO}_2 \times (1-\text{VD}/\text{VT})$) is applied to the measured values (VE L/min, $\dot{V}\text{CO}_2$ ml/min, STPD, PaCO_2 kPa). As shown in this figure, increased $\dot{V}\text{CO}_2$ due to hypermetabolism can markedly increase the ventilatory demand and even be the main component of it. Measurement of gas exchange can help to evaluate the cause of ventilator dependency.

FIGURE 16



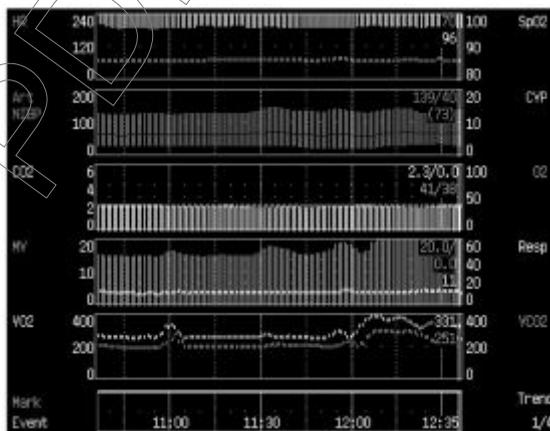
VE demand in ARDS

Increase in ventilatory demand

An elderly male patient was admitted to intensive care due to acute respiratory failure related to postoperative peritonitis and sepsis. He was intubated and mechanically ventilated on assist/control mode of ventilation. On the second day of intensive care, at 12:10 AM the patient had an acute increase in minute ventilation from 15 l/min to more than 20 l/min, while his end-tidal CO₂ and arterial oxygen saturation (pulse oximetry) remained stable. Physical examination did not reveal any relevant changes, except an acutely increased ventilatory drive, and arterial blood gas analysis confirmed unchanged PaO₂ and PaCO₂.

The CO₂-production had acutely increased from around 200 ml/min to more than 300 ml/min. This increase, related to an acute onset of bacteremia was the sole cause of the increase in ventilatory demand. The onset of sepsis may also worsen lung function and increase ventilatory demand also by increasing the VD/VT, although an unchanged end-tidal to arterial CO₂-ratio effectively excludes this possibility.

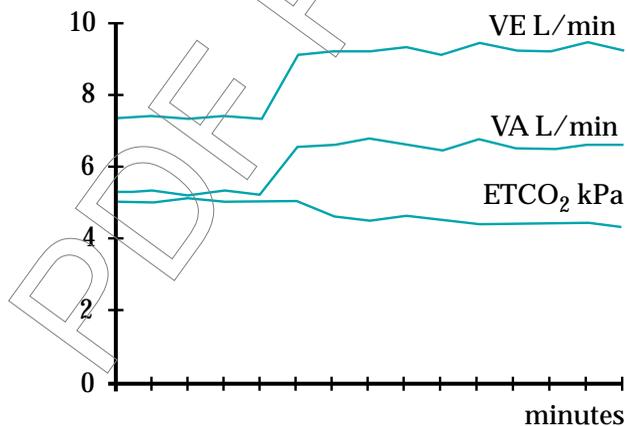
FIGURE 17



Measurement of alveolar ventilation

Figure 18: The Bohr's equation can also be applied to measure changes in alveolar ventilation in response to altered ventilator settings. The advantage of this technique is that the achieved level of alveolar ventilation is detected promptly, whereas changes in PaCO_2 or end-tidal CO_2 will continue, until a new steady state in the body CO_2 -pool has been achieved. Figure 14 demonstrates the change in VA in response to increased minute ventilation. The final level of VA could be observed in 2 - 3 minutes, whereas both end-tidal CO_2 (ETCO_2) and PaCO_2 will continue to change upto 60 - 90 minutes. By utilizing the gas exchange measurement, the response to major changes in ventilator setting can be observed more rapidly.

FIGURE 18

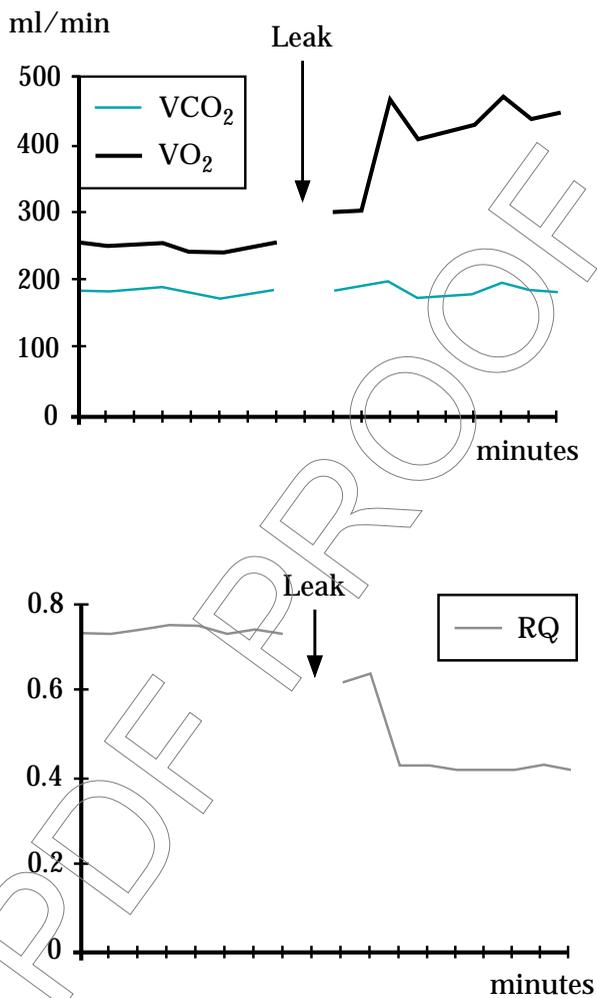


Effect of a change in ventilator settings on alveolar ventilation

Technical problems and physiological changes

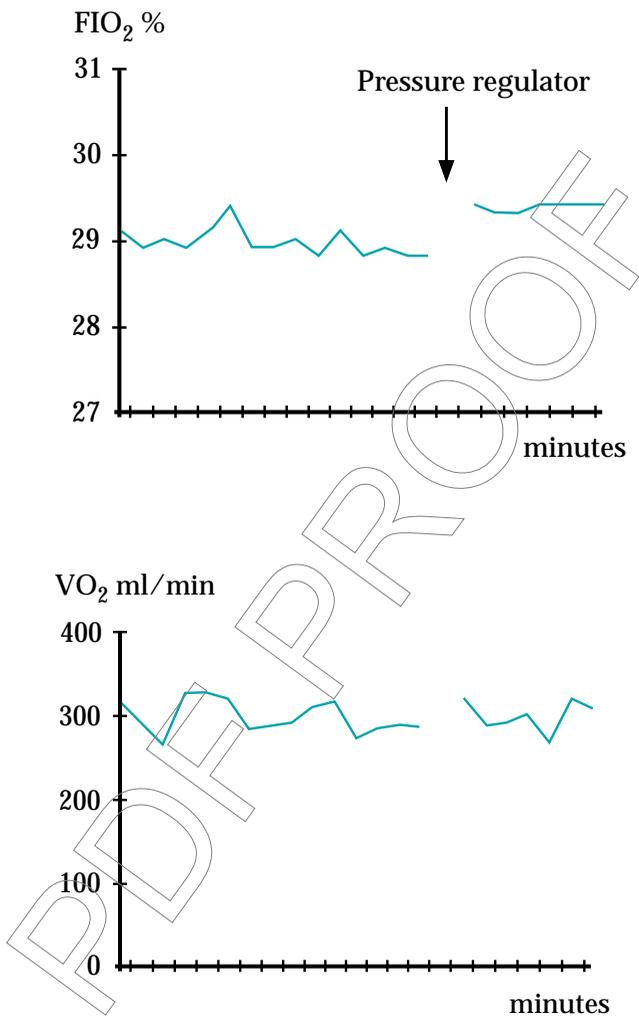
Figures 19-22: demonstrate some technical problems and physiological changes, which may interfere with the results or the interpretation. Figure 19 shows the artefactually high $\dot{V}O_2$ and low RQ, which result from a leak in the expiratory gas circuit. As shown, the effect on $\dot{V}CO_2$ is much smaller. Figure 20 shows a phenomenon, which is relatively common in hospital pressurized gas supply systems. The variation of pressure in the gas supply will influence the performance of the gas blender and result in varying FIO_2 . This is reflected in the measured $\dot{V}O_2$ as additional variation. The variation can be reduced by the use of pressure regulator, as shown in the figure. The remaining variation in the measured $\dot{V}O_2$ is mostly physiological, caused by variations in breathing pattern, which is common during ventilator modes allowing spontaneous breathing. This patient was on a low frequency synchronized intermittent mandatory ventilation with pressure support. The effect of the ventilator mode on the stability of FIO_2 is shown in figure 21. The relatively stable FIO_2 during controlled mechanical ventilation is markedly unstable, when the patient is switched to CPAP. Figure 22 demonstrates the wide variation in $\dot{V}O_2$ and $\dot{V}CO_2$ caused by rapid changes in the metabolic demands, in this case due to major epileptic seizures in a patient with intracranial injury. Other factors that may modify the metabolic demands include e.g. fever, pain, and anxiety. It is important to consider the potential alterations in the basic metabolic requirements, when results of gas exchange measurements are interpreted.

FIGURE 19



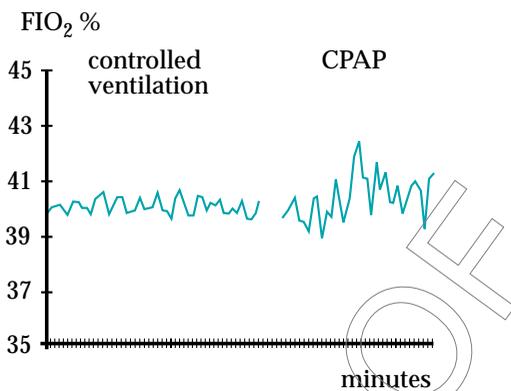
Effect of a leak in the expiratory gas circuit

FIGURE 20



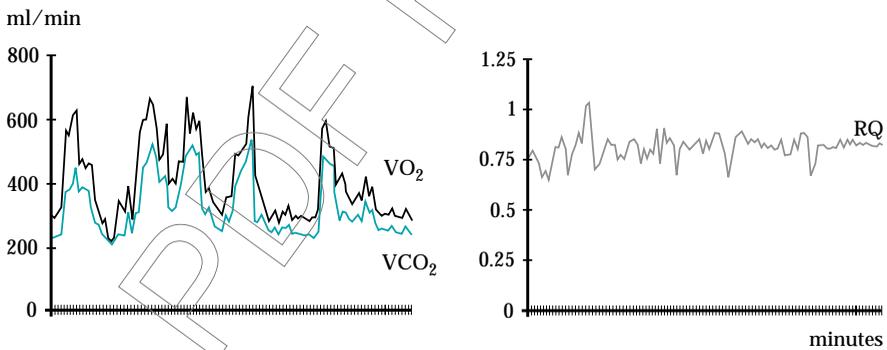
Reduction of FIO₂-variation with a pressure regulator

FIGURE 21



Effect of ventilation mode on the variation of FIO_2

FIGURE 22



Effect of epileptic convulsions on gas exchange

Summary

Portable instruments for measurement of gas exchange in the clinical setting have now been available for several years. This has increased our understanding of the nutritional requirements and response to nutrition in various disease states and opened up new insights to the pathophysiology and management of life-threatening respiratory and hemodynamic problems. The need to measure the actual energy expenditure in some groups of patients with prolonged nutritional problems has also become more evident. This progress will most likely make measurement of gas exchange an integral part of clinical monitoring in the intensive care unit. While the technology for accurate gas exchange measurements is available, accuracy and reproducibility of results requires understanding of the basic principles of the measurement technique, the underlying physiology, and that meticulous attention is paid to the details of the measurement procedure.

Suggested reading

Bursztein S, Elwyn DH, Askanazi J, Kinney JM (eds): Energy metabolism, indirect calorimetry, and nutrition. Williams & Wilkins, Baltimore, MD, USA, 1989

Snyder JV, Pinsky MR (eds): Oxygen transport in the critically ill. Year Book Medical Publishers, Inc. Chicago, London, 1987

Nunn JF: Applied respiratory physiology, 3rd ed. Butterworths, London, 1987.

Kinney JM, Fürst P, Elwyn DH, Carpentier YA: The intensive care patient. In: Kinney JM, Jeejeebhoy KN, Hill GL, Owen OE (eds): Nutrition and metabolism in patient care pp. 656 - 671. W.B. Saunders Company, Philadelphia 1988.

Bessey PQ, Wilmore DW: The burned patient. In: Kinney JM, Jeejeebhoy KN, Hill GL, Owen OE (eds): Nutrition and metabolism in patient care pp. 672 - 700. W.B. Saunders Company, Philadelphia 1988.

Rothkopf MM, Stanislaus G, Haverstick L et al: Nutritional support in respiratory failure. Nutrition in Clinical Practice 1989;4:166 - 172

Meriläinen PT: Metabolic monitor. Int J Clin Monit Comp 1987; 4:167 - 177.

Braun U et al: Evaluation of methods for indirect calorimetry with a ventilated lung model. Int Care Med 1989; 15:196 - 202.

Takala J, Keinänen O, Väisänen P, Kari A: Measurement of gas exchange in intensive care: Laboratory and clinical validation of a new device. Crit Care Med 1989; 17:1041-7.

Lanschot JJB van, Feenstra BWA, Vermeij CG et al: Accuracy of intermittent metabolic gas exchange recordings extrapolated for diurnal variation. Crit Care Med 1988;16:737 - 742

Schumacker PT and Cain SM: The concept of a critical oxygen delivery. *Intens Care Med* 1987;13:223 - 229

Shoemaker WC, Kram HB, Appel PL: Therapy of shock based on pathophysiology, monitoring and outcome prediction. *Crit Care Med* 1990;18:19 - 25

Askanazi J, Carpentier YA, Elwyn DH et al: Influence of total parenteral nutrition on fuel utilization in injury and sepsis. *Ann Surg* 1980;191:40

Roulet M, Detsky AS, Marliss E: A controlled trial of the effect of parenteral nutritional support on patients with respiratory failure and sepsis. *Clin Nutr* 1983;2:97

Shaw SN, Elwyn DH, Askanazi J et al: Effects of increasing nitrogen intake on nitrogen balance and energy expenditure in nutritionally depleted adult patients receiving parenteral nutrition. *Am J Clin Nutr* 1983;37:930

Pitkänen O, Takala J, Pöyhönen M et al: Nitrogen and energy balance in depleted patients undergoing major gastrointestinal surgery: response to TPN. *Clin Nutr* 1991;10:36 - 42

Grote AE, Elwyn DH, Takala J et al: Nutritional and metabolic effects of enteral and parenteral feeding in severely injured patients. *Clin Nutr* 1987;161 - 167

Jeevanandam M, Young DH, Schiller WR: Influence of parenteral nutrition on rates of net substrate oxidation in severe trauma patients. *Crit Care Med* 1990;18:467 - 473

Al-Saady NM, Blackmore CM, Bennett ED: High-fat, low-carbohydrate enteral feeding lowers PaCO₂ and reduces the period of ventilation in artificially ventilated patients. *Intens Care Med* 1989;15:290-5.