VENTILATORY PARAMETER MONITORING DURING INTENSIVE CARE HYPERBARIC TREATMENTS
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Introduction
The treatment of intensive care patients with hyperbaric oxygen requires skilled staff and a constant attention to haemodynamic, ventilatory and thermal parameters. Medical devices have been adapted to the hyperbaric environment, or alternatively, special medical devices have been developed that are little or not influenced by the environmental pressure changes. However, even if the medical device (automated syringe, artificial ventilator) does not change during the HBO session, the patient’s organism does react to the HBO environment.

Methods
Several ventilators of different types and brands have been proposed and tested for use in the hyperbaric environment(1, 2, 3, 4, 5).
Although there is no strict guideline or directive to describe the essential functional characteristics of a ventilator in hyperbaric environment, most authors agree that the “ideal” ventilator would have to be able to guarantee a ventilation under hyperbaric circumstances that is identical to the ventilation in normobaric circumstances, with as little operator-adjustments as necessary (6). Usually, this is expressed in terms of measurable mechanical or electrical parameters, such as: stability of tidal volume, stability of ventilatory rhythm, maintenance of flow, accuracy of pressure alarms, etc (7, 8). The certification process is a long and tedious one; to date, there is only one ventilator that has been officially CE certified for use in a hyperbaric environment (9).

Physiologically, however, adequate ventilation must be expressed in terms that related to the patients’ condition, i.e.: adequacy of carbon dioxide washout and of oxygen delivery to the arterial blood (10). Moreover, the mechanical ventilation may not interfere with the patients’ cardiovascular system performance.

In our Centre for Hyperbaric Oxygen Therapy, patients are treated in a large multiplace chamber (Haux StarMed 2800, Karlsbad, Germany) with a rectangular access door permitting the introduction of the patient on a regular ICU bed. Ventilatory support is provided by means of a Bird Avian transport ventilator (Bird Technologies, Palm Springs, USA). It is a time-cycled ventilator, where the ventilatory rate is not affected by changing I/E ratio. Therefore, as long as the inspiratory phase is shorter than the expiratory phase, the ventilatory rate does not change. The ventilator has controls for contiguous change in breath rate (0-150 bpm) flow-rate (5-100 L.min⁻¹), contiguous change in tidal volume (TV: 50-2000 mL), and high- and low-airway pressure alarms. It is capable of delivering controlled, control-assisted, SIMV and CPAP ventilation modes.
All controls and adjustments are made by rotation dials, unaffected by pressure. Various ventilatory modes are possible: controlled, pressure-support, volume-assist. Continuous monitoring of airway pressure is possible. There is no internal PEEP setting – PEEP is achieved by means of an external valve mounting. The ventilator functions on a dry-cell battery lasting for 11 hours when fully charged. It needs only 3.5 bar overpressure for the supply gas (oxygen or compressed air). It has been tested for safe use in hyperbaric environment (11).
This ventilator has been used in our centre for more than 6 years, and has proven to be an easy to operate, stable device. However, during each hyperbaric session a number of verifications have been deemed necessary to ensure that the ventilatory support is adequate in terms of pulmonary function. Each intubated patient is continuously monitored with invasive blood pressure and ECG (TRAMscope, Marquette Electronics, Florida, USA). A transcutaneous oxygen and carbon dioxide measurement (Radiometer TCM3, Copenhagen, Denmark) is affixed to the subclavicular skin. An arterial blood gas sample (ABG) is taken just before the start of the compression, and the arterial CO₂ pressure is correlated to the measured TcPCO₂. A mechanical spirometer (Dräger anesthesiology spirometer, Lubeck, Germany) is placed on the expiratory circuit, and if needed, a PEEP valve is attached. A parameter chart is filled in every 15 minutes, starting before the compression.

During compression, the Tidal Volume is checked against the expiratory volume (ExpV) measured mechanically. The TV setting is then adjusted to maintain a fixed ExpV. This can be done rapidly, almost on a breath-by-breath basis. Usually, at 2.5 ATA treatment pressure, the TV setting on the ventilator is more than doubled compared to the initial value.

The following possible pitfalls have been observed and are now added to the curriculum of continuous education for medical and paramedical personnel in our Centre.

1. **Inspiratory flow insufficiency.**
   As the external pressure changes, the inspiratory flow is reduced. This is not related to a reduction of the supply gas flow (which is provided at 6.5 bars absolute), but simply because of a reduced expansion of the breathing gas when exiting the ventilator into the inspiratory circuit. Even when adjusting the TV on the ventilator to maintain the desired ExpV, this effect causes a prolongation of the inspiratory phase, and the changing I/E ratio may affect the efficiency of ventilation. In patients with a high desired ventilatory rate, such as small infants, this may cause the I/E ratio to become unacceptable, at which point the ventilator gives an alarm and stays at a 1/1 ratio. It is therefore necessary to increase the flowrate on the ventilator, a change that usually in adults does not result in increased airway pressures (typically from 50 to 60 L.min⁻¹), but may become important in children (e.g. from 12 to 16 L.min⁻¹).

2. **Atelectasis**
   It is well known that pulmonary areas with partial atelectasis may well collapse completely during (even short-term) high-dose oxygen therapy (12, 13, 14). The same effect can sometimes be observed during HBO therapy, and should be readily noted as a progressive decline of the PtcO₂ values measured, with a constant PtcCO₂ value. Our experience is too limited to draw conclusions whether this happens predominantly in children or infants, but there seems to be a higher incidence in these categories, probably because of higher chest wall compliance (15). Although in routine, no PEEP valve was used (the slight increase of the resistance in the expiratory circuit gives a “native” PEEP of approximately 1 cmH₂O), it has now become standard practice to provide a PEEP level of approx. 5 cmH₂O in children, and to be prepared to add a PEEP valve in adults when atelectasis is suspected.

3. **PEEP pressure and impaired venous return**
   The addition of PEEP is not always beneficial. In patients with critical filling pressures and/or septicemia, venous return to the right heart may be impaired by the higher intrathoracic pressures (16). Symptoms typically include an increase in heart rate, and decrease of blood pressure. Inadequate ventilation results inevitably, with a decline in PtcO₂ and a rise in PtcCO₂. This may sometimes be attributed to other causes, such as shock or inadequate vascular filling,
or the administration of inotropic/chronotropic drugs. However, it should be reminded that during HBO therapy, usually the dosage of these medications can be reduced, and if the patient is relatively stable, should not have to be increased. A decrease in PEEP value should be attempted as a first measure, before increasing any IV drugs.

4. Ventilatory dead space in infants
Although the respiratory circuits used for infants have a considerably smaller volume than those used in adults (250 mL vs. 550 mL), the amount of ventilatory dead space must never be underestimated. Under normobaric conditions, up to 50 % of VT consists in dead space ventilation (17). It is to be expected that this is not different in the hyperbaric setting. It is therefore important that the respiratory circuit remains as small as possible. We have observed that the simple addition of a small extension tubing (additional volume of 30 mL) caused the ventilatory dead space to increase beyond effective ventilation in a 6-years old patient, ventilated at 30 x 150mL (normobaric). Not only does dead space decrease the effective exchange of fresh breathing gas in the pulmonary system, any increase of the breathing circuit’s length will cause the insufflated gas stream to become less cyclic, diminishing the effective distribution of gas in the alveoli and decreasing CO₂ washout (18).

As the ventilator used in the ICU is usually more complex and can not be used in a hyperbaric setting, a change of ventilator needs to take place. It is our policy to perform this change in the ICU chamber, and to ascertain the stability and efficacy of the new ventilation modalities before moving the patient out to the HBO chamber.

The importance of a complete and reliable patient monitoring during HBO therapy can not be underemphasised. Transcutaneous oxygen and carbon dioxide measurements are a most valuable tool, but must be verified against ABG samples before the start of the HBO session and at least once during the session. “Minor” technical details in normobaric circumstances may become very important in the hyperbaric setting, and it is important that the medical and paramedical staff be made aware of this. A simple example is the careful removal of all residual air in the ABG syringe immediately after sample taking, because during rapid decompression, the arterial blood will be exposed to a much larger air pocket with a very high driving force of blood gases out of the sample.

Conclusions
A thorough knowledge of the physics of the artificial ventilator used, as well as physiological mechanisms influencing oxygen uptake and transport in the human body, are needed to ensure a safe treatment of intensive care patients in the HBO chamber.

Although the search for the “ideal” ventilator for use in the hyperbaric chamber is a noble cause, and even though it is indeed desirable that the set ventilatory parameters change as little as possible during compression and decompression, this is by no means a guarantee for a good patient management. Especially from a medicolegal point of view, it is not sufficient to rely on a good ventilator, full stop. Besides theoretical knowledge of relevant changes in the respiratory system, training and experience in the management of ventilated patients are mandatory. Transcutaneous oxygen and carbon dioxide measurements, themselves double checked with serial arterial blood gas measurements, are essential to monitor the course of treatment. The parameters should be recorded and the parameter sheet added to the medical record of the patient upon his or her return to the ICU.
References