Review Articles

MEDICAL EQUIPMENT FOR MULTIPLACE HYPERBARIC CHAMBERS
Part II: Ventilators

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Kot J: Medical equipment for multiplace hyperbaric chambers. Part II: Ventilators. Europ J Underwater Hyperbaric Med 2006, 7(1): 9-12. All medical devices introduced into the hyperbaric chamber should be of an appropriate design and fit for use in the hyperbaric environment and the manufacturer should certify them for hyperbaric conditions. However, until now only several medical devices are CE marked for usage in hyperbaric chambers. Therefore users often need to perform themselves checking of the medical equipment needed for continuation of intensive care during hyperbaric treatment. To make this task easier, this paper presents review of reports of usage of medical devices under increased pressure. Part 1 concerned devices for monitoring and cardiac support. Part 2 describes mechanical ventilators and Part 3 will be devoted to infusion pumps and syringes.

Hyperbaric Oxygen Therapy, Medical Equipment, CE Marking

INTRODUCTION

In Part 1 of this paper (1) the review concerning monitoring devices and cardiac support was presented. This Part describes mechanical ventilators. Part 3 will be devoted to infusion pumps and syringes.

VENTILATORS

According to indications accepted for HBO therapy some sessions need to be conducted with intensive care or emergency patients. This means that general treatment of critically ill patients, including artificial ventilation, must be continued while inside the hyperbaric chamber. Therefore the hyperbaric chamber should be equipped with a pre-installed or transportable ventilator to support ventilation during HBO session.

Ideally, such device should ensure the same parameters and modes of ventilation as every ICU ventilator. However, the performance of all pneumatic devices inside the hyperbaric environment is changed by increased pressure and altered density of gases.

The ventilator is a generator of flow of breathing mixture (2). The flow of gas occurs between supply pressure of gas (P_{suppl}) and internal pressure inside respiratory system of the patient (P_{lungs}), where the driving pressure of the flow (ΔP_{flow}) is defined as:

$$\Delta P_{flow} = P_{supply} - P_{lungs}$$

Regardless of small changes during breathing phases, P_{lungs} is directly related to the environmental pressure ($P_{lungs} \approx P_{env}$). Therefore:

$$\Delta P_{flow} \approx P_{supply} - P_{env}$$

To keep the ΔP_{flow} independent from the changes of P_{env}, the P_{suppl} needs to be constantly corrected (3, 4).

The flow of gas depends not only on driving pressure but also on whether flow is laminar or turbulent (5). Several factors determine the type of flow and all of them are combined into Reynold's number (*Re*). The Reynold's number is a dimensionless value which can be calculated using equation:

$$\mathrm{Re} = velocity \times diameter \times \frac{density}{viscosity}$$

If *Re* is less than 2000 than the flow will likely be laminar. If *Re* is greater than 2000, flow will probably be turbulent.

The laminar flow is efficient as all layers of gas are passing smoothly over each other and for any given tube (constant radius and length) it depends directly on the driving pressure and is related to the viscosity of the gas according to relation:

$$Flow \propto \Delta P_{flow} \times \frac{1}{viscosity}$$

On the other hand the turbulent flow is less efficient due to multiple eddy currents occurring in the overall direction of flow. Such flow is related to the square root of the driving pressure and to the density of the gas according to relation:

$$Flow \propto \sqrt{\Delta P_{flow}} \times \frac{1}{density}$$

Viscosity of the gas depends mainly on its temperature and density depends mainly on the pressure. Therefore any increase of ambient pressure influences mainly turbulent flows by increasing the density of the gas. Additionally turbulent flows are very sensitive to any fluctuations of the driving pressure ΔP_{flow} (6).

Unless this phenomenon is technically compensated, the clinical consequences are hypoventilation due to decreased flow (7, 8) and/or increased work of breathing in any assist mode of ventilation (continuous positive airway pressure [CPAP] and pressure support ventilation [PSV]) (9, 10).

Knowledge of physical properties of gas under pressure and construction and type of operation of the ventilator helps in prediction of changes of its working parameters in hyperbaric environment.

In volume-controlled ventilation (VCV) the user selects parameters that define volume delivered, the time it takes to deliver the volume, and the flow waveform used during volume delivery (2). During inspiration the gas flow is kept constant on the preset level by internal adjusting the opening of the inspiratory valve. This mechanism works fine only in normobaric conditions, because relationship between inspiratory valve opening and volume flow is constant only for specified gas density. In hyperbaric environment, increasing of gas density by compression will cause the volume flow to decrease when the degree of valve opening is kept constant. Therefore the tidal volume supplied during the VCV decreases with the increase of ambient pressure (7, 8) or frequency decreases in order to prolong the inspiratory phase to inflate the circuit to the desired volume (4, 11). To compensate those changes during HBO sessions, it is necessary to continuously adjust a preset tidal volume according to independent monitoring of ventilation (by measurement of real expiratory tidal volume) or at least by nomograms. Some ventilators used for VCV are specially designed for hyperbaric use and the adjustment of the tidal volume delivered is done automatically. However, it should be emphasized that full compensation is possible for some range of pressures only, and this possibility strongly depends on the ventilator model.

In pressure-controlled ventilation (PCV) the clinician sets the target pressure and inspiratory time or I:E ratio (2). Because pressure is the target, tidal volume may vary from breath to breath, but is independent from ambient pressure. Any compression-induced decrease of the gas outflow from the inspiratory valve is compensated by the pressure control algorithm and the tidal volume remains stable at each ambient pressure (7). Therefore this kind of ventilators is preferred in hyperbaric conditions (7), even if their use has been discouraged by some authors in the past (8, 12). However, the user has to remember that pressure compensation mechanism of the PCV is limited to quite normal resistance of respiratory system of patient as well as certain range of ambient pressure (8).

The exact level of pressure-induced changes in ventilator's performance strongly depends on its type and technical design. Therefore it is almost impossible to precisely predict its performance while under pressure considering only physical laws and basic knowledge of its construction (7). The empirical data needs to be obtained under hyperbaric conditions for each particular ventilator type. Moreover, the compatibility of the ventilator with the hyperbaric conditions must be carefully checked to ensure that it does not create any unnecessary additional risk. For those reasons, standard ICU ventilators cannot be used inside hyperbaric chambers, unless they are modified for hyperbaric environment.

Up to now, only two ventilators have been CE certified for use in a hyperbaric environment. This is French ventilator RCH-LAMA and Italian ventilator Siaretron 1000 Iper (60 VF).

The RCH-LAMA (13) is a volumetric ventilator with pneumatic logic controlling inspiratory flow on a constant level (preset by user in a range of 3 to 21 L/min in 3 L/min steps) regardless of ambient pressure up to 6 ATA. Respiratory rate can be set in a range of 5 to 35 breaths per minute (with a step of 5 breaths/min) with a constant I:E ratio of 2. Maximum pressure inside the respiratory circuit is 20 to 80 mbar, and the PEEP can be set up to 10 mbar. There is also a possibility to set limit of the pressure inside the respiratory circuit. The ventilator is equipped with visual and audible alarms. The unit needs 12 V power supply (DC) and 10 bar overpressure of the supply gas to operate, as well as a pipe connection to the external ambient pressure as a reference. The ventilator is equipped with the system of automatic control of pressure in the balloon of the endotracheal tube (with calibration option). It is quite compact (40 cm x 14 cm x 19 cm) and light (8 kg) making it easy to install in the hyperbaric chamber.

Siaretron 1000 Iper (Iper 60 VF) (11) is an electropneumatic ventilator which has automatic compensation of the volume delivered up to pressure of 7 ATA measured by a special absolute pressure transducer. The ventilator can operate in IPPV, PSV, SIMV and CPAP modes and it has alarms for high and low airway pressure. The user can set the oxygen concentration (between 21 and 99%) as well as I:E ratio. The ventilator is supplied by the air and oxygen having pressure at 3.5 bar higher than pressure in the chamber. The electronic circuit is powered by low voltage batteries (2x6V) granting autonomy of about 3 hours.

There is also other ventilator – Hyperlog Draeger (11, 14, 15) – which has been constructed with automatic compensation of working parameters to the environmental pressure, however it has not been CE certified for use in hyperbaric environment. It is a pneumatically controlled volumetric ventilator with auto-compensation of changes in delivered volume due to compression and decompression. The user sets the minute volume (in a range of 3 to 20 L/min) and frequency (in a range of 1 and 40 breaths/min), while I:E ratio is fixed. The ventilator operates at a pressure of 10 bar of supply gas (air or oxygen) with a need for reference to external ambient atmosphere. It can be used up to 6 ATA. There is a visual indicator of pressure in the respiratory circuit, and delivered volume is checked by independent spirometer placed on the exhalation valve but there is no alarm of pressure or delivered volume. It is simple and compact (18 x 21 x 30 cm) ventilator lacking any sophisticated methods of ventilation needed for modern intensive care.

Several other ventilators have been modified to make their structure compatible with hyperbaric environment. They have been tested by users in different conditions most often with positive results. The list of ventilators which have been used in multiplace hyperbaric chambers is presented in the Table 1.

Table 1. Ventilators used in multiplace hyperbaric chambers

Ventilator	Testing conditions and comments	References
Ambumatic (Ambu Inc. Linthicum, MD, USA)	Can be used only for VCV. Tested to 2.8 ATA.	16
Bennett PR-2 (Puritan Bennett)	Can be used only for PCV. Controlling circuitry can be separated from the actuator and adjusted from outside the chamber.	11, 12
Bird Avian (Bird Technologies, Palm Springs, USA)	Can be used only for VCV. Tested to at least 2.5 ATA.	17
Campbell EV 500	Can be used only for VCV. Tested to 4 ATA.	18, 19
Emerson	Can be used only for VCV. Tested to 6 ATA.	11, 20
EVITA 4 (Drägerwerk, Germany)	Can be used for VCV and PCV. Tested to 2.8 ATA also in CPAP and PSV modes.	7, 9, 21, 22
Hyperlog (Dräger)	Can be used only for VCV. Tested to 6 ATA. It has automatic compensation of tidal volume for hyperbaric conditions.	14, 15, 23
Impact Uni-Vent Eagle Model 754 (Impact Instrumentation Inc., NJ, USA)	Can be used only for VCV. Tested to 6 ATA.	24
Lifecare PLV-100	Can be used for VCV and PCV. Tested to 6 ATA also in SIMV and assist modes.	25
Microvent (Drägerwerk, Germany)	Can be used only for VCV. Tested to 6 ATA.	7, 9, 21, 22
Monaghan 225	Can be used only for VCV. Tested to 6 ATA also in SIMV and assist modes.	11, 15, 23, 26
Newport Medical 300m (Newport Medical Instruments Inc., CA, USA)	Can be used for VCV and PCV. Tested to 6 ATA.	24
Ohio 550	Can be used for VCV and PCV. Tested to 4 ATA.	12
Omni-Vent Series D (Allied Healthcare Products, Inc., USA)	Can be used only for VCV. Tested to 6 ATA.	24
Oxylator EM-100 (Livesaving Inc., USA)	Can be used only for PCV. Tested to 4 ATA.	27
Oxylog (Dräger)	Can be used only for VCV. Tested to 3.5 ATA.	11, 14, 28, 29
Oxylog 2000 HBO (Drägerwerk, Germany)	Can be used only for VCV. Tested to 2.8 ATA also in CPAP mode.	7, 9, 21, 22
Penlon Multivent (Penlon Ltd, Abingdon, Oxfordshire, UK)	Tested to 6 ATA.	24
Penlon Oxford (Penlon Ltd, Abingdon, Oxfordshire, UK)	Can be used only for VCV. Tested to 6 ATA in air and to 31 ATA in heliox atmosphere.	11, 30, 31, 32, 33
PneuPAC HC (Sims PneuPAC Ltd, UK)	Can be used only for VCV. Tested to 6 ATA.	15, 23
RCH LAMA (Laboratories de Mechanique Applique, Egly, France)	Can be used only for VCV. Tested to 6 ATA. It has automatic compensation of tidal volume for hyperbaric conditions. It is CE marked for hyperbaric use.	13
Servo 900C (Siemens-Elema, Sweden)	Can be used for VCV and PCV. Tested to 6ATA.	7, 9, 10, 21, 22
Servo 900C (Siemens Corp., Denmark)	Can be used for VCV and PCV. Tested to 4 ATA (RNTT67) using heliox 50:50.	34
Servo 900D (Siemens)	Can be used for VCV and PCV. Tested to 6 ATA also in assist and inspiratory support ventilation modes.	35, 36
Servovent 99 D (Siemens Elema AB, Solna, Sweden)	Can be used for VCV and PCV. Tested at least to 2.2 ATA.	37
Siaretron 1000 Iper (60 VF) (Bologna, Italy)	Can be used only for VCV. Designed for 7 ATA also for SIMV and CPAP modes. It has automatic compensation of tidal volume for hyperbaric conditions. It is CE marked for hyperbaric use.	38, 39
TXP (Percussionaire Corp., USA)	Can be used only for PCV.	12

It should be kept in mind that usage of those devices inside hyperbaric chamber needs constant adaptation of settings as depending of the environmental pressure to assure proper ventilation. It is especially important in the VCV, when the tidal volume delivered to patients usually decreases with increasing ambient pressure. Unless the ventilator has the automatic function for compensation this phenomenon, the user needs to adjust the tidal volume during any changes of pressure. Results of such modifications should be carefully and constantly evaluated. For this reason the PCV is preferable in hyperbaric conditions due to the stable tidal volume.

Regardless of the type of ventilator used for artificial ventilation there is a need for independent control by monitoring of gas exchange, at least by measurement of expiratory volume and partial pressure of carbon dioxide in expiratory gas. In most cases of critically ill patient additional monitoring of cardiorespiratory status is also necessary in mechanically ventilated patients including heart rate, arterial blood pressure and transcutaneous partial pressure of oxygen.

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