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ORIGINAL ARTICLES

VENTILATOR FUNCTION UNDER HYPERBARIC CONDITIONS

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Key Words

Equipment, hyperbaric research, ventilators.

Abstract

Assisted ventilation in the hyperbaric chamber presents challenges and risks due to machine and patient related problems. These problems and how to minimise them are discussed. The requirements of the ideal ventilator for use under pressure are detailed and so far few ventilators have satisfied these requirements.

Introduction

In addition to diving related injury, hyperbaric oxygen (HBO) therapy is used in the treatment of some critically ill patients for whom ventilatory support is often required (Table 1). The indications for endotracheal intubation and mechanical ventilation may include acute respiratory failure, the need for airway patency and protection from aspiration due to loss of airway reflexes and for the manipulation of blood pH. Currently accepted indications for hyperbaric oxygen therapy have been reviewed by Jain[1] and are beyond the scope of this paper.

The use of hyperbaric oxygen in the treatment of critically ill patients requires prolonged respiratory support in the chamber. Little information exists, in the respiratory and hyperbaric literature, both on the use of ventilators under hyperbaric conditions[1-6] and the evaluation of individual ventilators under hyperbaric conditions.

TABLE 1

DISORDERS WHERE VENTILATORY SUPPORT UNDER HYPERBARIC CONDITIONS HAS BEEN INDICATED

Cerebral air embolism
Decompression illness
Carbon monoxide poisoning
Smoke inhalation
Closed head injury cerebral oedema
Cyanide poisoning
Near drowning
Severe sepsis
Multiple trauma

The majority of patients receiving ventilatory support require augmentation of alveolar ventilation to decrease the work of breathing in hyperbaric chambers. No outcome data exists to guide the choice of ventilatory support in hyperbaria.

Assisted ventilation in the hyperbaric chamber presents challenges and risks due to machine or patient related problems. The characteristics of particular ventilators need to be understood to appreciate the likely degradation of performance under hyperbaric conditions.[7] The majority of ventilators used in chambers are pneumatically controlled and time cycled. The characteristics and physiological effects of these ventilators are reviewed below.

To use a ventilator safely the hyperbaric specialist must be able to predict any changes that may affect ventilator function under hyperbaric conditions in order to choose the most appropriate ventilator for the patient's needs. This can only be done with a thorough understanding of ventilators and how they function.

Ventilators used in the hyperbaric environment

Intermittent positive pressure ventilation (IPPV) did not receive widespread use until the 1950s when positive pressure ventilation was used effectively on patients during the polio epidemics in Denmark and Sweden. During this period ventilators were also shown to be reliable for use during anaesthesia and for post-operative ventilatory support.

The first published reports of ventilator function under hyperbaric conditions appeared in the mid 1970s.[8] In 1982 Saywood et al. recommended the use of the Penlon Oxford ventilator as it maintained a set tidal volume up to 6 bar of air and up to 31 bar ATA in oxy-helium.[9]

Ventilator classification

A ventilator is a device used to move gas into the lungs. The classification of ventilators has been confused by various authors producing different classifications.[10-14]

Two aspects of performance are particularly important when classifying a mechanical ventilator.

1 Functional characteristics, which include factors controlling the pressure and the flow rate of the gas delivered to the patient.

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TABLE 2

VENTILATOR CLASSIFICATION BASED ON PHASES OF THE MECHANICAL CYCLE

1 **Inspiratory Phase**
  Flow generation
  Pressure generation
2 **Inspiration to Expiration trigger (Cycle)**
  Pressure cycled
  Volume cycled
  Time cycled
3 **Expiratory Phase**
  Positive end-expiratory pressure (PEEP)
  Negative end-expiratory pressure (NEEP)
4 **Expired to Inspired trigger**
  Intermittent mandatory ventilation (IMV)

2 Operational features, which include its power source (electrical, pneumatic, spring tension or weighted bellows), patient circuit, alarm capability, controls and the provision of special modes of ventilation, e.g. positive end expiratory pressure (PEEP) and continuous positive airway pressure (CPAP).

It is now generally accepted that the most useful classification of ventilators for clinical application is according to the phases of the cycle.[15] Table 2 summarises this classification.

Inspiratory Phase (Gas Flow Production)

Inspiratory gas flow occurs when the proximal airway pressure is higher than alveolar pressure. In the non-breathing person tidal volume may be produced by flow or pressure generation.

FLOW GENERATORS

Constant flow generators produce flow at a constant rate despite changing pulmonary compliance throughout the inspiratory phase and therefore need to be powered by a high pressure source. The larger the pressure gradient between the gas source and the alveolar pressure the less effect the airways and pulmonary impedance will have on the flow. For these the airway pressure will vary accoding to the changes in pulmonary compliance. An example of such a constant gas flow generator is the IMV-Bird. This ventilator has relatively low driving pressures and output and would be expected to deteriorate significantly under hyperbaric conditions. The Bear 1, Bear 2 and Bennett 7200 ventilators have higher working pressures (up to 50 times the physiological alveolar pressure) and are less prone to deteriorate at pressure. In most Australian intensive care units ventilators are of the constant flow generator type.

Non-constant flow generators, such as the rotary driven piston Engström 150 ventilator, permit variable gas flow throughout the inspiratory phase of ventilation.

PRESSURE GENERATORS

A constant pressure generator ventilator maintains a constant pressure regardless of changes in pulmonary impedance. Ventilator pressure can be adjusted to provide the inspiratory pressure needed to deliver the required tidal volume.

A non-constant pressure generator will permit variable pressure during inspiration.

Cycling from inspiration to expiration

Cycling refers to the change from inspiratory to expiratory phases. Ventilators may be pressure, volume or time cycled. The limits of these various options may be preset. Pressure cycled ventilators are most commonly used for IPPV and short term ventilator support whereas volume cycling is more common during anaesthesia.

Pressure cycled ventilators, which terminate flow when a preset pressure is reached, may have controls which alter the cycling pressure. Tidal volume may vary with pulmonary compliance. Large leaks may cause the machine to fail to achieve the desired cycling pressure. Most pressure cycled ventilators use compressed air or oxygen at 50 psi (340 kPa or 3.4 bar) to power a venturi flow generating device. The volume of entrained gas is dependant on the ambient/venturi pressure gradient. Under raised pressure they may lack sufficient flow and pressure capabilities to ventilate the patient adequately.

Volume cycled ventilators deliver a preset volume of gas to the circuit. In its simplest form this is done by compressing a bellows. The pressure will build up to overcome any obstruction until the preset volume has been delivered. This may be a disadvantage in the hyperbaric environment due to volume expansion with ascent. A safety blow-off at 30-50 cm water is usually built in to the patient circuit to prevent pulmonary overpressure.

Time cycled ventilators have a timing mechanism which is not influenced by the condition of the patients lungs. With all ventilators inspiratory time needs to be limited to prevent cardiac output being reduced by too long a period of raised intrathoracic pressure. Inspiratory flow rate becomes a limiting factor under hyperbaric conditions. In the chamber an increase in ventilator rate is usually seen, because, as inspiratory flow becomes maximal, the timing circuit pressurises faster and cycles sooner.

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Fluidic Ventilators

Barila, and other anaesthetists from the Walter Reed Army Institute of Research, evolved the first fluidic ventilators in 1964. Fluidic systems such as the Campbell Mark 2 use moving streams of gas to perform sensing and control functions without mechanical moving parts. When a high speed stream of gas emerges from a nozzle it entrains surrounding gas causing a local fall in pressure and drawing further gas into the stream. When a fixed wall is placed close to the jet it is less easy for further gas to enter so the pressure quickly falls on that side pulling a pivoted jet over against the wall, the “Coanda effect”. This system has the advantages of no wear from moving parts and no electronics, so it is exceptionally safe in flammable environments and is not affected by moderate temperature changes or vibration. The disadvantages are that it is sensitive to dust contamination, has a relatively high consumption of driving gas and is noisy.

Clinical considerations for ventilator use under hyperbaric conditions

There is no evidence in the literature of normobaric IPPV that any particular wave form gives a better clinical outcome. No such work in hyperbaria has been reported.

When using a ventilator in the chamber the most important consideration is the ability of the ventilator to deliver clinically acceptable minute volumes to the patient. This will be determined by the behaviour of the ventilator under pressure and whether ventilator output is significantly affected by changes in the patient’s lung and chest wall compliance. Inspiratory and expiratory cycling characteristics change under hyperbaric conditions and tidal ventilatory requirements may increase.

To understand the relationship between ventilator performance under pressure and the effect individual patient lung compliance has on ventilator gas flow requires further information on the physiological effects of IPPV.

Effects of IPPV on patients

During intermittent positive pressure ventilation (IPPV) under normobaric conditions there is an increase in the ratio of physiological dead space to tidal volume. In spontaneously breathing patients physiological dead space is usually less than 30%. It may reach values of 40-70% in ventilated anaesthetised patients. This may become the limiting factor in the critically ill patient at pressure. Satisfactory tidal volumes will not be achieved, with resultant hypercapnia, unless tidal volumes can be increased.

Pulmonary compliance normally varies with age, body position and a number of pathological conditions. Even under normobaric conditions, there is a fall of about 50% in compliance with the commencement of IPPV. I have been unable to find any reports about the effect of IPPV on compliance under hyperbaric conditions.

Positive pressure ventilation changes the normal physiological responses to spontaneous ventilation. Changes in the haemodynamics of venous return, cardiac output, pulmonary circulation and its distribution (ventilation/perfusion relationship) during normobaric IPPV are well reviewed in respiratory texts[14,16-18] and are beyond the scope of this review. I have not been able to find any controlled studies on the effect of IPPV on ventilation/perfusion relationships under pressure.

Breathing is more difficult at higher pressures because gas density (the number of molecules packed into a given volume) is increased in direct proportion to absolute pressure and this movement of denser air requires more effort (work) to move.

Increased respiratory resistance at depth leads to increased energy cost of breathing increasing oxygen requirement, carbon dioxide retention, dyspnoea, sometimes adverse cardiovascular changes.

Figures 1 and 2 illustrate the relationships between increased gas density and the development of CO_2 retention and increased oxygen requirement. The cardiovascular changes under hyperbaric conditions are beyond the scope of this review.

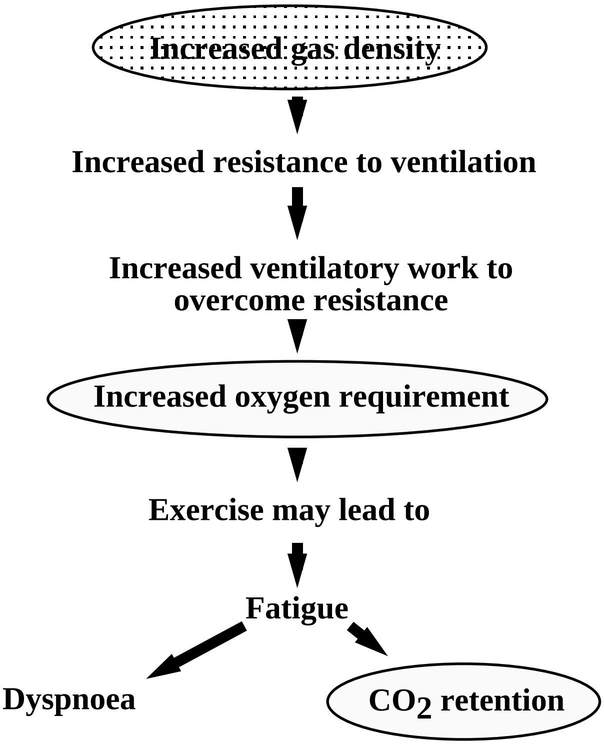

Figure 1. Model for normal subject at depth

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Work of breathing in the hyperbaric environment

During spontaneous ventilation, because the inter-pleural space (between lung and chest walls) only contains a thin fluid layer, the lungs follow the outward movement of chest and diaphragm generating a sub-ambient intrathoracic pressure. Inspiration occurs as air flows into the chest at atmospheric pressure. Diaphragmatic ventilation provides approximately 60% of tidal ventilation and chest wall expansion the remaining 40%.

The study of human work performance under hyperbaric conditions has been well documented in the awake normal subject. The increase in spontaneous minute volume under hyperbaric conditions corresponds to the increased oxygen requirement and the primary reason for this is the increase in respiratory resistance due to the alteration in gas density.[19]

Critically ill patients already have increased metabolic demand, with substantially higher oxygen requirements and invariably have respiratory muscle fatigue. The work of breathing in these patients is also increased by reduced lung compliance. The relative hypoventilation that occurs in this situation can place an excessive demand on spontaneously breathing patients. IPPV in these patients will relieve the excess work of ventilation. The energy expended by the ventilator is best described as the work required to overcome the increased breathing resistance.

PEEP under hyperbaric conditions

Many critically ill patients also require positive end-expiratory pressure (PEEP) to maximise oxygenation. Positive pressure on the airway at the end of expiration reduces hypoxia, limits alveolar collapse and decreases the amount of intrapulmonary shunting. However PEEP increases dead space, impedes venous return, increases the risk of barotrauma and can reduce cardiac output. The therapeutic range of PEEP is 5-40 cm H_2O. The Monaghan ventilator PEEP function operated well under hyperbaric conditions when tested by Moon in 1984.[20]

Youn et al. reported on PEEP valves in 1991. All the tested valves increased the level of PEEP by 2-4 cm H_2O as pressure increased. This was due to the increased gas density not to increased flow. They found that the valves had to be adjusted when pressure changes occurred to maintain the original level of PEEP. They recommended the Emerson water column PEEP valve which had demonstrated the least rise in pressure with increasing chamber pressure and this did not change with as pressure was raised further. This valve is cheap and easy to adjust. PEEP valves that cannot be adjusted should not be used in hyperbaric chambers. PEEP may subject the patient to an increased risk of barotrauma unless airway pressure is constantly monitored and the valve adjusted to maintain a steady level of PEEP.[21]

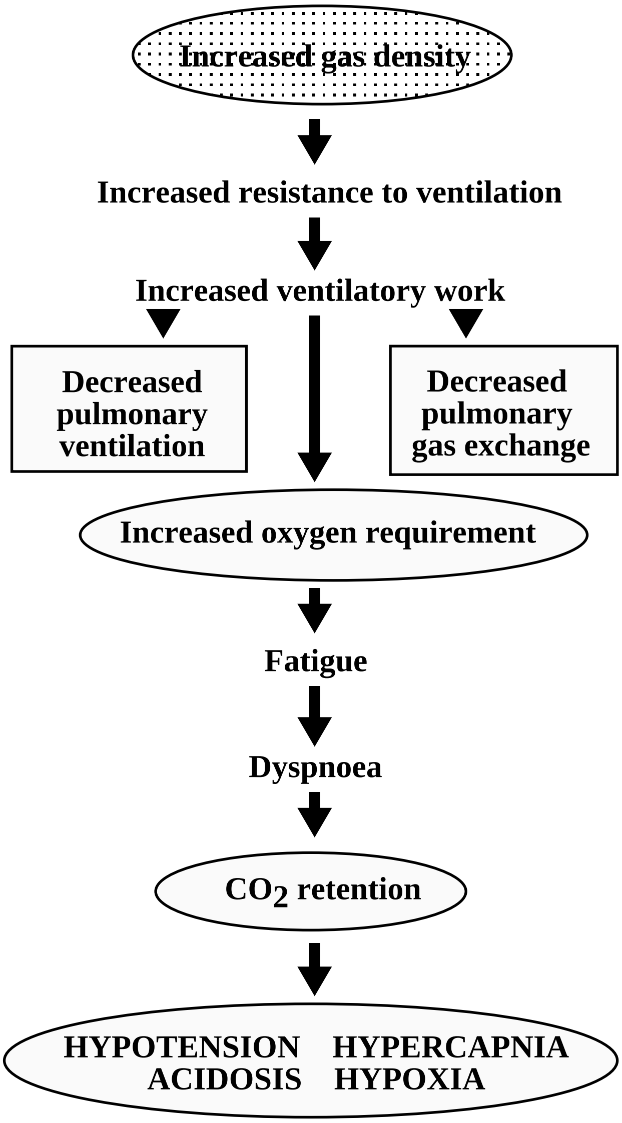

Figure 2. Model for respiratory compromised subject at depth

Intermittent Mandatory Ventilation

Intermittent mandatory ventilation (IMV) is used for spontaneously breathing patients still attached to, but not triggering, a ventilator. If the minute volume falls below a predetermined figure the ventilator cuts in to make up the preset volume. This mode must be used with caution in the hyperbaric environment as “stacking” of breaths may occur and could produce barotrauma from hyperinflation.

Respiratory heat loss during ventilation in the hyperbaric environment

At surface pressure (1 bar), breathing dry gases, respiratory heat loss accounts for about 10% of metabolic heat production. This is primarily through evaporative heat loss in the upper airway while saturating the dry inspired gas to a water vapour pressure of 47 mm Hg (6 kPa). At

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depth the inspired gas is denser and higher in heat capacity. Helium mixtures increase this heat loss as helium has 6 times the thermal capacity of nitrogen and 5 times its thermal conductance. The increased respiratory heat loss which has been shown, in normal individuals breathing very cold air at sea level as well as under extreme hyperbaric conditions (25 bar) breathing heliox, is induced by the high thermal capacity of helium.[22]

Physiological studies of divers revealed that significant heat loss occurs via respiratory tract when breathing helium containing mixtures[23,24] this heat loss is a major threat to diver safety and performance.

I have been unable to find clinical data, or outcome studies, on the effect of respiratory heat loss during mechanical ventilation under hyperbaric conditions at “standard” HBO treatment depths (i.e. at pressures < 6 bar).

ETCO$_2$ monitoring under hyperbaric conditions

The reduction in tidal volume provided by ventilators under pressure makes it necessary to monitor the adequacy of minute ventilation. Volume measurements give volume delivered or exhaled but not the adequacy of ventilation. End tidal CO$_2$ (ETCO$_2$) is the most informative monitoring of the physiological adequacy of an individual’s ventilation. Moon, in 1988, recommended that, because of the limitations of ventilators used under hyperbaric conditions, direct arterial CO$_2$ monitoring should be used during treatment.[25] However, with the development of end tidal C0$_2$ (ETCO$_2$) monitoring arterial puncture is no longer necessary. In 1992 Handell et al. used the Siemens infra red CO$_2$ analyser 930 to provide direct measurement of whether the preset minute volume ventilation was matched to the patient’s ventilatory needs. They concluded that end tidal CO$_2$ monitoring is a valuable tool in the hyperbaric treatment.[26]

Characteristics of the ideal hyperbaric ventilator

The provision of ventilatory support in the hyperbaric environment has created unique difficulties and the ideal hyperbaric ventilator does not yet exist. However, attempts have been made, e.g. Dräger Hyperlog. Few recommendations have been made in the literature about standards for the “ideal” hyperbaric ventilator. Moon recommended that hyperbaric ventilators should deliver a preset tidal volume at a constant rate and over an ambient range from 1-6 bar.[25]

The ideal ventilator should provide an unchanged pattern of ventilation or, at a minimum, provide a combination of tidal volume, ventilatory frequency and I/E ratio within clinically acceptable limits, for both adults and children, to depths where treatment will occur.

Ventilators used in the hyperbaric environment should have no external or internal electrical requirements that might provide a fire hazard. They should have an ability to deliver a wide range of tidal volumes at clinically relevant rates. Standard operating procedures in multiplace hyperbaric chambers require the fractional inspired oxygen (FIO$_2$) in the chamber to remain below 0.25, therefore exhaled gases from patients and ventilators must be vented outside the chamber.

Other desirable features include:
Robust construction.
Economical to purchase and run.
Simple to operate and maintain.
Clearly marked and simple to use controls.
Gas driven.
Provision for manual ventilation in an emergency.
Ventilation range 1-20 l/min.
Tidal volumes between 50 and 1,500 ml at frequencies between 5-50/min.
An alarm system to notify failure to achieve adequate ventilation.
Positive pressure during expiration when desired.
Humidification of inspired gas.
Easy to clean and sterilise.
Suitable for paediatric use.

Ventilator function under hyperbaric conditions

At constant absolute temperature, the volume of a given mass of a gas varies inversely with the absolute pressure (Boyle’s Law). This basic gas law is of considerable importance in understanding the use of ventilators under hyperbaric conditions. In monoplace chambers any ventilator placed outside the chamber will be limited by this law. As the pressure within the chamber increases the tidal volume delivered diminishes.

With ventilators in hyperbaric chambers gas flow rates are proportional to the gas density so as the ambient pressure increases the flow rate will fall. When the ambient pressure is increased to 2 bar (10 m gauge) density is double that at the surface.

Jaffrin and Kesic reviewed the fluid mechanics of pulmonary gas flow and found that when the pressure was doubled (to 2 bar) the actual flow was 71% of indicated flow.[27] With a constant orifice the pressure gradient required for a given flow will be greater under hyperbaric conditions, i.e. pressures will read high but flow delivery will be less than set.

The major component of mechanical resistance in the ventilator system is the resistance to flow which, in turn, is depenent upon the gas density. Increases in airway resistance affect IPPV by increasing the inspiratory time constant. Under hyperbaric conditions the power of the

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ventilator, i.e. its maximum capacity to deliver a set volume, may be insufficient to overcome the resistance to flow causing inadequate ventilation. It may be impossible, in some ventilators, to achieve adequate ventilation even using a prolonged inspiratory time setting. With no change in the expiratory time, or with an inadequate inspiratory/expiratory time (I/E) ratio, air trapping may result, with an increased risk of barotrauma and impaired gas exchange.

Ventilator gas flow under hyperbaric conditions

The capacity of a ventilator to maintain performance under hyperbaric conditions is dependant on its power reserve. The increase in gas density (D) is proportional to the increase in environmental pressure (P_{ata}) by the formula:

$$D = D_o \times P_{ata}$$

where D_o is the specific density of the gas.[6,7]

At a given volume V and at a pressure P, the compressibility of the gas (G_c), is defined by the modification of the volume per unit of pressure according to the equation:

$$G_c = V/P$$

Using Boyle's Law one can derive:

$$G_c = V/P_{ata}$$

i.e. if the volume remains constant then as the pressure increases the more the compressibility of a gas decreases. The increased gas density produces a decrease in flow from the orifice, the size of which is controlled by a needle valve.

Flow of a gas in a smooth tube is normally laminar until a "critical flow rate" is reached when it becomes turbulent. For a given flow rate, the resistance and pressure gradients required are greater for turbulent flow than for laminar flow. Narrowing in a tube forces the gas to accelerate which produces eddies and turbulent flow.

The Hagen-Poiseuille equation correlates the factors that determine laminar flow:

$$\text{Flow (Q)} = \pi P d^4/128hl$$

Where

P = pressure difference across the tube,
d = diameter of the tube,
l = length of the tube
h = viscosity of the gas. In the therapeutic range of pressures viscosity of fases rmains constant.

The theory of turbulent flow is complex. However the property of a gas which most influences turbulent flow in a hyperbaric environment is its density (r) and the pressure needed to produce a given flow will increase as the density increases.

The probability of turbulence can be predicted by an index known as the Reynolds number which is calculated according to the formula:

$$\text{Reynolds number} = nrd/h$$

where
n = velocity,
r = density,
d = diameter of the tube,
h = viscosity

As the density increases the Reynolds number also increases and turbulent flow becomes more likely and eventually predominates. Studies have shown that in 9 mm diameter endotracheal tubes flow will become turbulent when flow rates exceed 9 l/min. In 15 mm tubes (equal to the tracheal diameter) flow will become turbulent at 15 l/min and in 22 mm tubes (delivery tubing) it will become turbulent at 22 l/min.[28] Turbulent flow requires higher airway pressures to achieve adequate ventilation and this will be worse under hyperbaric conditions when ventilating with air and less so for helium.

Studies of ventilator function under hyperbaric conditions

Reports of assessment of ventilator function under raised pressure first appeared in 1977.[30] Table 3 summarises the studies I have found.[6,8,9,20,25,29-37]

1977 Ross and Manson assessed the behaviour of three portable ventilators/resuscitators under hyperbaric conditions.[29] These were the "Pneupac" Ventilator/Resuscitator, the "Motivus" Resuscitator (Type PV) and the "Stephenson Minuteman" Resuscitator. None provided adequate ventilation at pressure. The first two are time cycled, volume limited flow generators and neither was able to provide an adequate tidal volume at 2.0 bar. The Stephenson Minuteman ventilator is a pressure cycled flow generator. Tidal volume was adjusted using the unit pressure regulator. It delivered 100% oxygen at a constant tidal volume but at a reducing ventilatory frequency as the pressure increased. It was clinically unacceptable because the minute volume fell. The unit was incapable of producing a ventilatory rate greater than 6 a minute at 3 bar (20 m).

Gallagher et al. evaluated the IMV Bird and Mark 2 Bird up to 2.8 bar and showed that neither ventilator could maintain a tidal volume of 1,000 ml. They also evaluated modified IMV Bird and modified Mark 2 Bird ventilators using a test lung. At 4 bar (30 m) these units failed to provide a tidal volume of 1,000 ml.[8]

Moon tested 3 models of the Bird Ventilator and all failed at 3-4 bar.[27] These ventilators tended to be unstable during periods of changing ambient pressure. Moon also found the pneumatic Emerson ventilator delivered constant tidal volumes up to 6 bar (50 m). This ventilator used a leather bellows with a hydrocarbon lubricant which is well recognised as hazardous in hyperbaric conditions.

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TABLE 3

STUDIES OF VENTILATOR FUNCTION UNDER HYPERBARIC CONDITIONS

Note. Failed = unable to deliver clinically acceptable tidal volume

Year Author	Ventilator	Notes	Hyperbaric conditions
1976 Campell[37]	Campbell Mark 1	Stated to work satisfactorily	No data reported.
1977 Ross and Manson[29]	Pneupac Ventilator-Resuscitator	Time cycled and volume limited flow generator	Failed at 2.0 bar
	Motivus Resuscitator	Time cycled and volume limited flow generator	Failed at 2.0 bar
	Stephenson' Minuteman	Pressure cycled flow generator 6 breaths/minute at 3 bar	Failed at 2.0 bar
1978 Gallagher, Smith and Bell[8]	IMV Bird	Unstable with changing pressure	Failed at 2.8 bar
	Mark2 Bird	Unstable with changing pressure	Failed at 2.8 bar
1979 Moon[25]	Bird Various models		Failed at 3-4 bar
	Emerson Ventilator	Bellows with hydrocarbon lubricant	Constant tidal volume (TV) up to 6 bar
1982 Saywood et al.[9]	Penlon Oxford	Volume cycled	Constant TV to 6 bar for air and to 31 bar for heliox.
1987 Lewis et al.[31]	Penlon Nuffield 200	Pneumatic time cycled flow generator. Modification needed	Adequate TV at 1.8 bar
1989 Hipp et al.[32]	Siemens Servo 900B	Internal electrical components potential electrical hazard	Adequate to 3 bar
	Siemens Servo 500C		
1986 Moon et al.[20]	Monaghan 225	PEEP function tested	Maintained preset TV to 6 bar
1989 Blanch, Desautells and Gallagher[33]	18 Various ventilators	Pneumatic time cycled, pneumatic pressure cycled and volume cycled	Necessary to have minute volume monitoring
1991 Spittal, Hunter and Jones[34]	Pneupac HB	Time cycled, constant flow Set tidal volume	16 l/min at 2.5 bar
1992 Gibson, Davis and Wilkinson[35]	Pneupac HC	Pneumatic controlled time cycled Adjustable	Functioned to 6 bar
1990 Dragerwerk[36]	Drager Hyperlog	Time cycled pneumatic specifically designed for hyperbaric use	Limits not stated No reports of function
1992 Oriani, Marroni and Wattel[6]	Iper 60VF	Electropneumatic time cycled	Assured ventilation in assist/control mode

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The Penlon Oxford, a volume cycled ventilator, was tested by Saywood to 6 bar (50 m) in compressed air and to 31 bar (300 m, 1,000 ft) in a helium/oxygen environment.[9] The rate and delivered tidal volume was stable over the entire pressure range. At the time it was, reportedly, the only commercially available ventilator to maintain rate, tidal volume and inspiratory time under hyperbaric conditions. Youn in 1989 combined the Penlon 200 Ventilator with the Ohmeda volume monitor to provide rate, volume, apnoea and minute ventilation data.[30]

Lewis et al. assessed the Penlon Nuffield 200 Ventilator, a pneumatic time cycled flow generator, for HBO treatment, in a monoplace chamber, of carbon monoxide (CO) poisoned patients.[31] Modification was necessary to achieve adequate tidal volumes.

Hipp et al. reviewed the Siemens Servo 900B ventilator at pressures up to 3 bar.[32] They found that the delivered minute volume decreased continuously with increasing chamber pressure and that the display of minute volume showed falsely high values. Despite these limitations it has been used by these authors for hundreds of hours without malfunction. The Siemens Servo 500C has also been used; however the internal electrical components make this ventilator a fire hazard which has reduced its use.

The Monaghan 225 ventilator was used extensively at Duke University Medical Center and tested by Moon et al. in 1986 for use in a hyperbaric chamber.[22] It was found to maintain preset tidal volume to 6 bar and deliver clinically acceptable maximum minute ventilation. It delivered 38 l/min at 1 bar reducing to 18 l/min at 6 bar. PEEP functions were tested to 6 bar and operated well. However the preset respiratory rate decreased as the pressure was raised. This was the first “off the shelf” ventilator, with these features, shown to function well under pressure. It is driven by compressed oxygen.

In 1989 Blanch et al. published studies 18 different mechanical ventilators, grouped as pneumatic time cycled, pneumatic pressure cycled or volume cycled (piston or bellows) ventilators.[33] They recommended that clinicians measure the delivered tidal volume after any significant alteration in chamber pressure.

The Pneupac range of ventilators has been accepted widely for resuscitation and anaesthesia. These ventilators are time cycled, constant flow generators capable of delivering a set tidal volume irrespective of airway resistance and lung compliance. When initially tested under hyperbaric conditions the tidal volume decreased exponentially with ambient pressure and the frequency increased linearly until performance was inadequate.

The Pneupac HB was designed specifically for monoplace hyperbaric chambers and its performance was reviewed by Spittal et al. in 1991.[34] The ventilator delivered minute volumes of 11-23 l at 1 bar and 7.6-16 l at 2.5 bar.

The Pneupac HC Hyperbaric Ventilator was specifically designed to ventilate patients over a range of pressures up to 10 bar. The ventilator is a pneumatically controlled, time cycled ventilator providing independent control of inspiratory time, expiratory time and flow rate. It is also autocompensated for pressure by a pneumatic system and can be fed with air or oxygen. Gibson et al. carried out a calibration of this ventilator to derive a series of tables for its clinical use.[35] They found it to be a robust ventilator with consistent performance that could provide clinically appropriate tidal volumes for the vast majority of adult patients up to 6 bar. It is cheap and simple to operate and is capable of providing clinically significant tidal volumes to common treatment depths.

The Dräger Oxylog has been well proven as a robust and capable ventilator. It is generally limited to 2 bar but its advantage is that it does not need modification of any kind. The Dräger Hyperlog, designed for use under hyperbaric conditions, is simple to operate and no adjustments are required with changes in pressure.[36] This is important for critical care nurses who may use these machines infrequently. It works well with air, oxygen or heliox, however there is no IMV mode and it has no alarms.

The Iper VF60 is an electropneumatic, time cycled ventilator which has a variable I/E ratio. The pneumatics are supplied at 3 bar with variable FIO_2 capability. The electrical circuit is low voltage and low resistance. An environmental pressure sensor automatically compensates the gas feed pressure and respiratory control.[6]

Campbell stated that the Mark 1 ventilator had been used under hyperbaric conditions with success,[37] but I am unable to find such a report. It requires continual adjustment during pressure changes. It is not easy to use as there are no set marks for identification of inspiratory times, expiratory times or flow, only graduations.

The Sechrist 500A ventilator is a commonly used in chambers in the United States. It is a compact but delivers less than the preset tidal volume whenever ventilator compliance load falls and is severely limited if chamber pressure is greater than 2 bar. It requires a driving pressure of at least 450 kPa to operate normally. This exceeds the usual hospital wall outlet oxygen pressure of 350-400 kPa.

The Bird Mark 7 has also been used in Australia but modifications have been required. No literature reference for its use under hyperbaric conditions has been identified. This machine is oversensitive and difficult to operate but provides a cheap alternative to other more expensive models.

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Summary

For volume cycled ventilators the change from inspiratory to expiratory phase occurs when a certain tidal volume has been supplied. Under hyperbaric conditions the increase in resistance reduces flow. Increased inspiratory time is therefore needed to supply a given tidal volume. Therefore a decrease in ventilatory frequency (breaths/min) occurs with a reduction in minute volume.

For pressure cycled ventilators the change from inspiration to expiration occurs after a given pressure level is reached. Due to the increase in resistance at increasing hyperbaric conditions, tidal volume is reduced as the cycling pressure is more rapidly achieved.

Time cycled ventilators represent the majority of current ventilators. In these the timing chamber of the pneumatic circuit senses the effect of reduced compressibility of the gas and will cycle more quickly, reducing inspiratory and expiratory time. As the pressure rises reduction in tidal volume and increase in ventilator rate is seen.

The selection of an optimal I/E ratio on the ventilator is important to avoid elevated end expiratory pressures. Inspiratory pressure will vary and understanding of the altered lung mechanics in ventilated patients and the altered ventilator mechanics is essential to operate a ventilator safely under pressure.

Future research

In the last 15 years developments in mechanical ventilatory support have allowed patient initiation of ventilator function via various modes.[15] The original modes of mechanical ventilation (control and assist/control) provide full ventilatory support[38] and are the norm under hyperbaric conditions. The introduction of IMV and proportional assist ventilation allow partial support and newer modes include pressure support and airway pressure release.

No clinical data presently exists for the use of such modes in the hyperbaric environment and this area provides a challenge for further research.[39]

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This paper formed part of the thesis submitted for the Diploma of Diving and Hyperbaric Medicine awarded to Dr M W Skinner in November 1997. When the Diploma was awarded he was Provisional Fellow in the Department of Anaesthesia and the Hyperbaric Medicine Unit at the Fremantle Hospital, Fremantle, Western Australia 6160.

ASSESSMENT OF THE CAMPBELL “D-MODE” VENTILATOR UNDER HYPERBARIC CONDITIONS

Marcus Skinner

Key Words

Equipment, hyperbaric research, ventilators.

Introduction

The Royal Hobart Hospital commissioned a new Hyperbaric Chamber in February 1993. Since that time a review of in-chamber equipment has been undertaken. A Penlon 200 is used in this facility and a backup ventilator was needed. An assessment of currently available ventilators for use in the chamber was carried out.[1] A Campbell D Mode ventilator was made available for assessment by ULCO Engineering. No performance reports on the function of Campbell ventilators under hyperbaric conditions have been identified in the literature.

Methods

The Campbell D-Mode Portable ventilator is an Australian made pneumatic, time cycled, volume and rate preset, constant flow generation ventilator developed by ULCO Engineering. Its driving gas supply is medical air or oxygen supplied at 60 psi (415 kPa) gauge of which it consumes 1 l/min in addition to the minute volume. The ventilator was assessed under normal and hyperbaric conditions. Its ability to deliver a preset volume or rate was assessed at three pressures.

At 1 bar it delivers tidal volumes from 50 ml to 2,000 ml with inspiratory times of 0.5-2.0 seconds and expiratory times ranging from 1.0-6.0 seconds. Timing is controlled by graduated scales. Inspiratory time for the ventilator, on each of its graduations, was measured using a digital stopwatch (average of five readings) at each pressure.

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The ventilator was attached to a Siemens test lung (compliance rated at 50 ml/cm H_2O/l) to simulate a patient's lung. The manufacturer states that the specific compliance of normal lung is in the region of 60-70 ml/cm H_2O/l.

A Wright's respirometer, calibrated using a 2 litre Rudolph gas calibration syringe, was used to measure tidal volumes at 1 bar (surface), 2.4 bar (14 m) and 2.8 bar (18 m). Calibration at 1 bar and 2.8 bar showed that the Wright's Spirometer over-read the tidal volume by an average of 6% at low volumes and by 3% at high volumes. The recordings have been adjusted to reflect this error.

The "D" Mode ventilator flow control was set at 1.0, 0.75 and 0.5 and the tidal volume measured for each inspiratory time setting (0.5, 0.75, 1.0, 1.25, 1.5 and 2.0 seconds). Expiratory time was left at the 2.0 seconds setting for convenience and to allow for a greater than 1:2 inspiratory to expiratory (I/E) ratio. The setting of the expiratory time does not affect the inspiratory time setting. The tidal volume at each inspiratory time setting was measured three times and averaged. These measurements were repeated at each pressure.

From the data obtained a series of graphs indicating the tidal volume for given ventilator settings and tidal volume at maximal flow for three depths was constructed. A further graph depicting the minute volume at maximal flow was constructed for each depth.

Results

The results of the study are shown in Figures 1-5. The narrow variation within each group of readings reflects the consistent performance of the ventilator. Figures 1-3 present the tidal volumes achieved for different flow settings over the ventilator's range of inspiratory times at 1 bar, 2.4 bar and 2.8 bar. Figure 4 presents the tidal volumes achieved at these three depths at maximal flow. Figure 5 presents the minute volumes achieved at these three depths for maximal flow.

It is clear that the performance of the Campbell D Mode ventilator decreases with pressure as at 1 bar it delivers more than twice the volumes available at 2.4 bar and approximately three times the volumes available at 2.8 bar. To achieve a minute volume of 10 l at 2.4 bar, flow must be set to maximum and inspiratory time to at least 1.25 seconds with an expiratory time of two seconds. At 2.8 bar a minute volume of 10 l cannot be achieved.

Discussion

As would be expected for a pneumatic, time cycled, constant flow ventilator the performance of the Campbell D Mode ventilator decreased significantly as the chamber

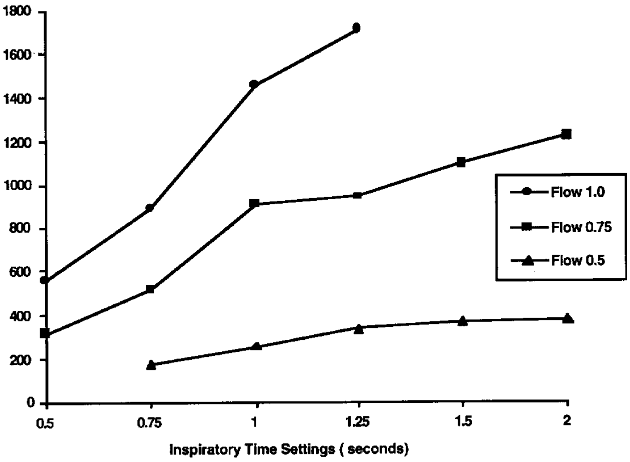

Figure 1. Tidal volumes at 1 bar for each inspiratory time setting (0.5-2 seconds), with the expiratory time constant at 2 seconds, for three flow settings (0.5, 0.75 and 1).

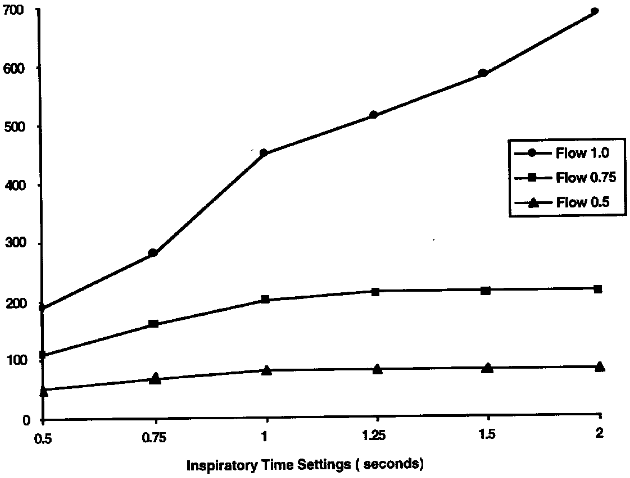

Figure 2. Tidal volumes at 2.4 bar for each inspiratory time setting (0.5-2 seconds), with the expiratory time constant at 2 seconds, for three flow settings (0.5, 0.75 and 1).

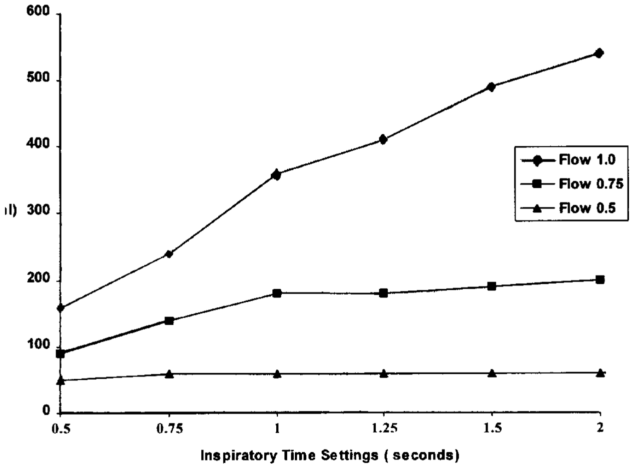

Figure 3. Tidal volumes at 2.8 bar for each inspiratory time setting (0.5-2 seconds), with the expiratory time constant at 2 seconds, for three flow settings (0.5, 0.75 and 1).

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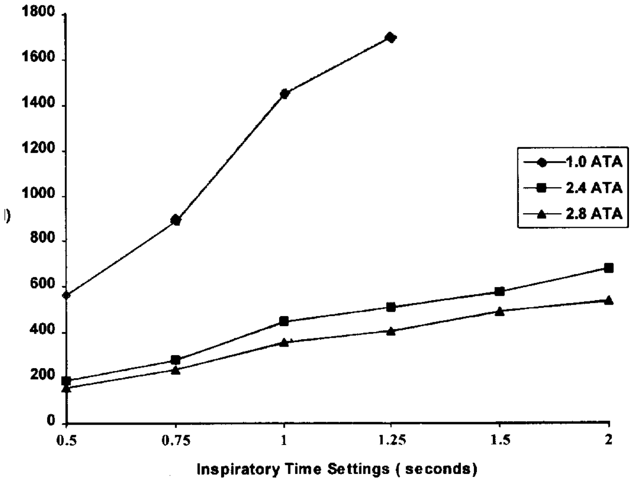

Figure 4. Tidal volumes for each inspiratory time setting (0.5-2 seconds), with the expiratory time constant at 2 seconds, for the maximum flow setting (1) at 1. 2.4 and 2.8 bar.

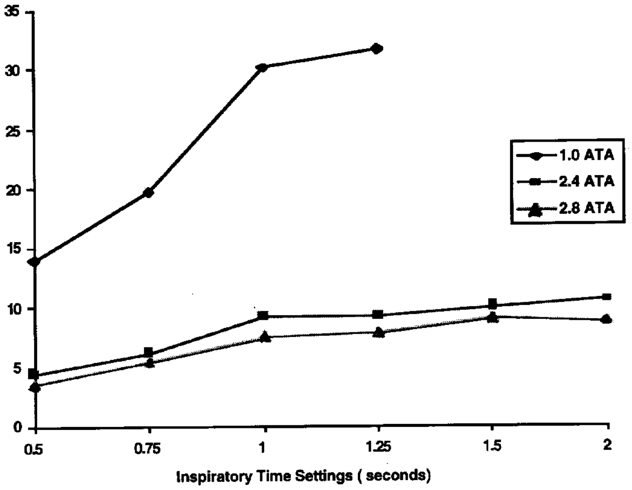

Figure 5. Minute volumes for each inspiratory time setting (0.5-2 seconds), with the expiratory time constant at 2 seconds, for the maximum flow setting (1) at 1. 2.4 and 2.8 bar.

pressure increased. Such changes have also been documented for the Oxford Penlon 200 ventilator.[2] The Campbell D Mode does not approach the extended range or the reported performance of the Pneupac HC hyperbaric ventilator.[3]

It is apparent that the Campbell D Mode ventilator is incapable of providing clinically acceptable tidal volumes to the average adult patient at pressures beyond 2.8 bar (18 m). At the Royal Hobart Hospital facility patients are routinely treated at 14 m (2.4 bar) and 18 m (2.8 bar). At the maximal flow setting (1.0) and with the inspiratory time setting of 1.0 second and an expiratory setting of 2 seconds (I/E Ratio 1:2) the tidal volume was 460 ml at 2.4 bar and 380 ml at 2.8 bar. With the inspiratory time increased to 1.5 seconds these values increased to 590 ml and 500 ml respectively. In order to maintain clinically acceptable minute volumes in patients the tidal volumes must be monitored and the rate adjusted accordingly. This requirement has been mentioned in other studies in which the minute ventilation was measured by a suitably calibrated spirometer.[3-6]

In clinical practice the delivered tidal volume may alter with changing lung compliance, whereas in this study the test lung compliance remained unaltered. It is accepted that patients' lung compliance may alter, particularly in the critically ill patient. In previous studies the clinical significance of changes in patients lung compliance at depth and its effects on positive pressure ventilatory tidal volumes was not investigated.

Use of the Campbell D Mode ventilator on patients in our chamber suggests that the changes in patient lung compliance at pressures of 2.8 bar are of minimal significance. This ventilator was not designed specifically for hyperbaric use. When considering the aspects required of the ideal hyperbaric ventilator[1] the Campbell D Mode is robust, simple to operate and easy to maintain. The controls are clear and simple to use with well defined graduations. It has visual and auditory disconnect alarms and may operate on air or oxygen. The ventilator driving gas (oxygen) pressure remains constant at depth and has no significant influence on the delivery of an adequate tidal volume.

The inspiratory and expiratory times of pneumatically time cycled ventilators, including the Campbell D Mode, shorten with increasing ambient pressure.

The Campbell D Mode ventilator has been found to be an acceptable alternative to the Penlon 200 that has been in use in our chamber. It has the same disadvantages as the Penlon but has the major advantage of being capable of being preset by dialling up set graduations on the machine. This has been found helpful for Intensive Care ventilator trained staff who use the ventilator only occasionally. Spirometry is used in the clinical setting and adaptation for end tidal CO_2 monitoring is being undertaken.

Conclusions

The desirable features of the ideal hyperbaric ventilator have been proposed elsewhere.[1] The Campbell 'D' Mode ventilator meets some of these requirements. It is robust and simple to operate and maintain. The driving gas can be air or oxygen. The ventilator's controls allow for known values to be set. A warning system for disconnection or reduced inspiratory pressure is part of the ventilator.

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The Campbell D Mode ventilator provides an alternative to the Penlon 200 for the average adult patient. However it does not achieve the desired maximal inspiratory flow rate of 80 l/min at depth (2.8 bar) where its maximum flow is only 35 l/min. At 2.8 bar tidal volumes above 600 ml cannot be achieved. It would be unable to provide clinically acceptable tidal volumes in some clinical circumstances (e.g. the morbidly obese) and further studies are needed to identify its clinical limits.

The PEEP function has not been evaluated. Controlled ventilation in the hyperbaric chamber presents a variety of challenges and risks that require further evaluation.

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THE WORLD AS IT IS

1997 ANNUAL MEETING OF THE AUSTRALIAN HYPERBARIC TECHNICIANS AND NURSES ASSOCIATION

Eric P Kindwall

Key Words

Hyperbaric facilities, meeting.

The Coogee Beach Hotel was the venue for the 5th Annual Scientific Meeting of the Australian Hyperbaric Technicians and Nurses Association (HTNA) 28-30 August 1997. Coogee Beach is a pleasant seaside suburb of Sydney, which in August was welcoming the beginning of spring “down under”. There were well over 100 participants from the nine hyperbaric facilities in Australia, all hospital-based units with multiplace chambers. More than 30 papers were submitted to the meeting; slightly over half of them dealt with clinical hyperbaric medicine and the remainder with diving-related subjects. Laura Josefson, RN, President of the BNA, and I were guests of the HTNA and were given ample time to speak on the program.

The clinical hyperbaric subjects were broad and varied. They included impaired neutrophil adhesion in patients with diabetes, the problem of claustrophobia in the chamber, injury mechanisms in carbon monoxide poisoning, psychiatric profiles of patients with carbon monoxide poisoning, a survey of middle ear barotrauma in unconscious patients, an update on the results of hyperbaric incident monitoring (the HIMS Study) and the use of tympanostomy tubes.

The divers dealt with the treatment of decompression sickness, DCS at very shallow depths, technical diving subjects and the practicality and utility of square hyperbaric chambers.

We were met at the airport by Dr Ian Unsworth, literally the founder of HBO therapy in Australia, who turned us over to the capable hands of John Kershler and Barrie Gibbons of the Prince of Wales Hospital HBO unit, who had made all our travel arrangements.

The highlight of the trip for me and my family was a grand tour of the hyperbaric facilities in Australia, starting in Sydney with the Prince of Wales Hospital and HMAS PENGUIN, the Royal Australian Navy Diving Training Facility. Our travels then took us to the Royal Hobart Hospital in Hobart, Tasmania; the Alfred Hospital in