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Colonel (Dr) Jimmy How Yew Chen is the Senior Medical Officer, Republic of Singapore Navy.

His address is 50 Bayshore Road, Aquamarine Tower #14-06, Singapore 1646, Republic of Singapore.

PROJECT STICKYBEAK

This project seeks to document all types and severities of diving-related accidents. Information,which is treated as being CONFIDENTIAL in regards to identifying details, may be sent to:

Dr D. Walker
P.O. Box 120, Narrabeen,
N.S.W. 2101,Australia.

ASSESSMENT OF THE PNEUPAC HC HYPERBARIC VENTILATOR

A.J. Gibson, F.M. Davis and A.R. Wilkinson

Introduction

The PneuPac HC Hyperbaric Ventilator (Figure 1) has been specifically designed to ventilate patients within hyperbaric chambers over a range of pressures up to 10 ATA (atmospheres absolute). It is a standard pneumatically controlled, time-cycled ventilator providing independent control of inspiratory time, inspiratory flow rate and expiratory time. The range of these parameters has been significantly extended to allow compensation for the changes in ventilator performance with different chamber pressures.[1] Following the manufacturer's advice, we carried out calibration of the PneuPac HC ventilator to derive a series of calibration tables for its clinical use.

Description of PneuPac HC ventilator

The HC Ventilator consists of a pneumatic control module operating a remote patient valve housed in the patient connection block. These are linked by a small diameter flexible hose which can be separated to allow sterilisation of the patient valve. The control module is operated from compressed air, oxygen or a helium/O_2 mixture which is delivered from a regulator within the chamber, set at 400-1000 kPa gauge pressure. A simple schematic diagram of the PneuPac HC is shown in Figure 2.

The control module has three control knobs; one each for the inspiratory and expiratory times which are each arbitrarily graduated from one to nine, and an inspiratory flow control which completes eight and a half revolutions between its minimum and maximum settings. As well, there is an on/off switch and a pressure gauge. All moving parts of the control module are manufactured to require no lubrication or maintenance.

On connecting the ventilator to the gas supply and switching on, the spool in valve B is initially biased to allow the gas to flow from port 1 to port 2 from where it will flow to the inspiratory timer valve C and to valve F and thence to the patient valve.

The inspiratory time knob restricts the gas flow into the inspiratory timer cartridge C which then fixes the rate of pressure rise within C. At a predetermined pressure, a piston within C moves to allow gas to flow to port 4 of valve B which in turn switches the spool of valve B to the expiratory position. Now the gas flow is directed from port 1 to port 3 and thence to the expiratory timer cartridge D which behaves in a similar way to the inspiratory cartridge. During expiration, a non-return valve within C opens to release the pressure within this cartridge. The expiratory time knob is

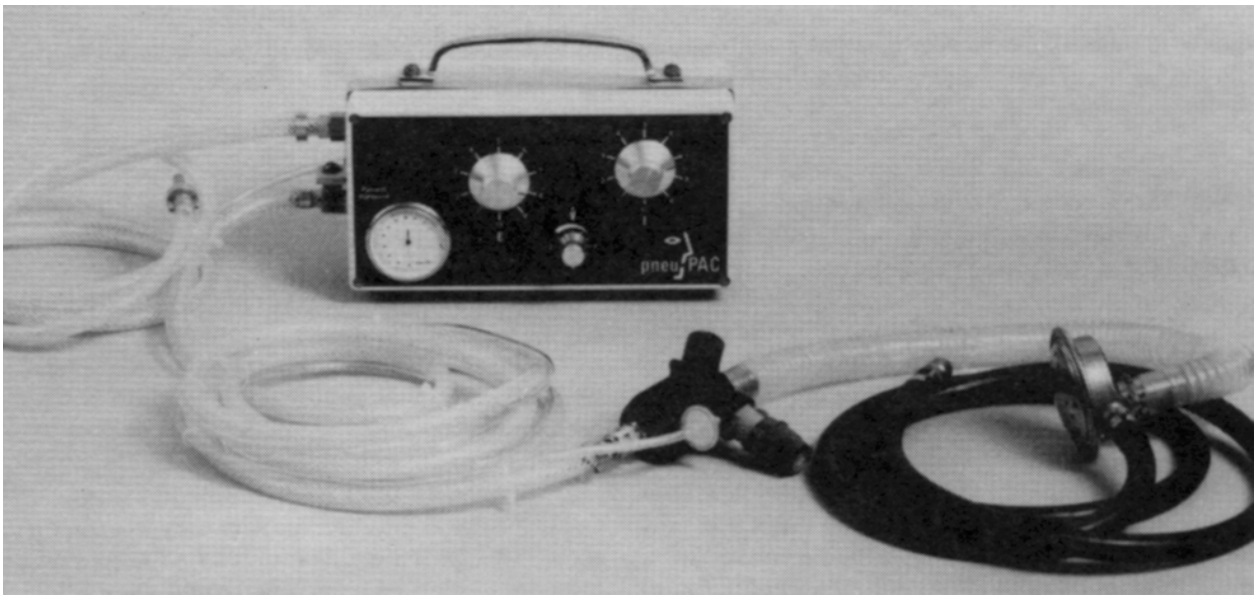

Figure 1. ThePneuPac hyperbaric ventilator control box showing (from left to right) the inflation pressure gauge, expiratory time control (E), flow control(V) and inspiratory time control (I). The patient control valve is in the middle foreground with the overboard dump system via a Scott exhalation regulator on the right.

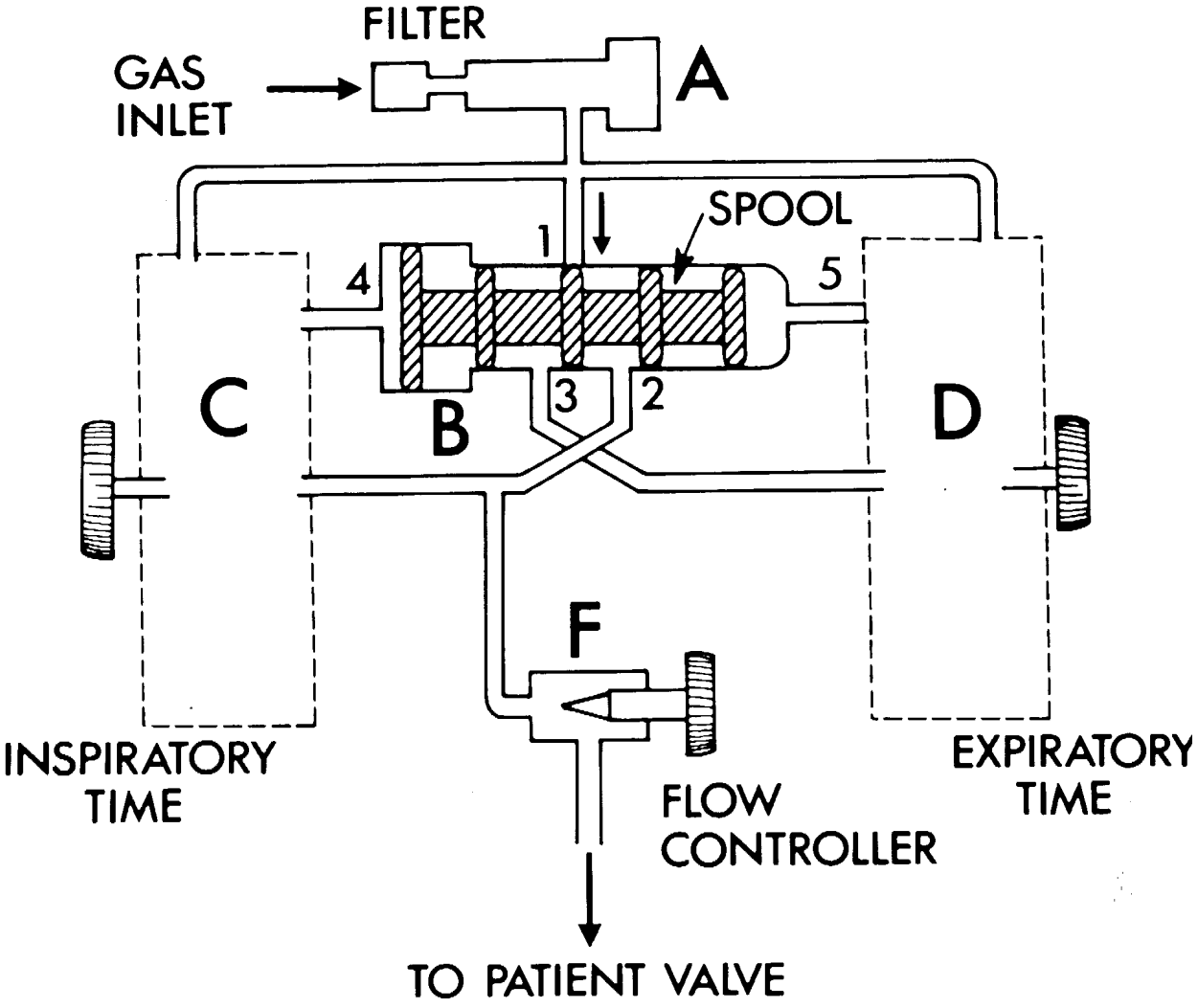

FIGURE 2. Schematic diagram of Pneupac HC ventilator. See text for explanation of terms.

adjusted to control the expiratory time and is used together with the inspiratory time to determine the desired respiratory rate for the patient.

During inspiration, gas is delivered to valve F, one side of which is connected to the flow controller and thence to a reducing valve, the other side to the gas outlet and thence to the patient via the patient valve.

The patient valve operates by using the pressure energy in the gas flowing from the control module. During inspiration, the gas flow to the patient valve passes through an orifice which causes the pressure to drop to patient pressure. The resultant pressure on the end of a piston pushes it against a spring which closes the exhaust port and connects the patient to the gas flow from the orifice. The patient is protected from over-inflation by a pressure relief valve (two are provided, with blow-off pressures of either 40 or 60 cm H_2O). During expiration, the spring forces the piston back to open the exhaust port, the patient exhaling through the valve and out the exhaust port. The patient valve is fail-safe in that should the module be switched off or the gas supply fail, the valve opens to the atmosphere.

Methods

The PneuPac HC ventilator was tested using a simple circuit which included a calibrated Wright's spirometer and a "mock lung" over a range of inspiratory time and flow settings at 1.9 ATA, 2.8 ATA and 6 ATA.

CALIBRATION OF WRIGHT'S SPIROMETER

Using a 2 litre Rudolph gas calibration syringe, the volumes recorded by a Wright's spirometer were checked at each pressure. This was done by taking the average of three readings in 200 ml steps up to 2000 ml, each tidal volume being delivered in approximately one second.

INSPIRATORY TIMES

With a digital stopwatch, the inspiratory time for the ventilator on each of its graduations on the inspiratory time control was measured at each pressure. For each time setting, the inspiratory time was taken as the average of five readings.

DELIVERED TIDAL VOLUME

For each inspiratory time graduation, the flow control was then adjusted from its minimum to its maximum setting (eight-plus revolutions) with the tidal volume being measured using the spirometer. Five readings were taken at each complete revolution between the minimum and maximum settings and averaged. Throughout the measurement of tidal volume, the expiratory time was left on its maximum setting for convenience, since changes in its setting did not influence the inspiratory time. The temperature and humidity within the chamber were also recorded. These measurements were repeated at each pressure.

Results

Calibration of the Wright's spirometer at 1.9 and 2.8 ATA showed that it consistently over-read the tidal volume by approximately 8% at low tidal volumes (< 500 mls), reducing to 5% at higher tidal volumes. This error was slightly greater (11% down to 6%) at 6 ATA. Subsequent recordings of the tidal volumes measured from the ventilator were corrected by these factors and standardised for temperature and humidity.

Inspiratory times progressively shortened with increasing ambient pressure, such that they were on average about 35% shorter at 6 ATA than at 1.8 ATA. At 6 ATA the longest inspiratory time that could be achieved was 1.25 sec. Expiratory times at any given setting shortened with increasing pressure in a similar manner. Ventilation rates down to about 12 breaths per minute were still achievable at 6 ATA. We found that the clinically useful inspiratory times (0.75 - 1.5 sec) were within the control setting range from 6 to 9.

The tidal volume at each setting was measured five times and averaged. There was seldom more than 10 ml variation within each group of readings, demonstrating consistent performance of both the ventilator and the spirometer. As an example, Table 1 gives the results for the tidal volumes generated at 50 m depth for each of the inspiratory time settings as the flow rate is increased stepwise by one revolution of the flow control from its minimum to its maximum setting. At lower chamber pressures, readings were not taken at the longer inspiratory times at high flow rates as the tidal volumes generated were well beyond the clinically useful range. Similar tables were constructed for 1, 1.9 and 2.8 ATA pressures.

Figures 3, 4 and 5 represent graphically the data at each of the 3 depths for a minimum, intermediate and maximum flow setting, over a clinically useful range of inspiratory times.

Discussion

As would be expected for a time-cycled pneumatically-controlled ventilator, the performance changes as the chamber pressure is increased or decreased. Blanch et. al.[1] have described the performance characteristics of a range of ventilators under hyperbaric conditions. The changes observed by us with the PneuPac HC are closely consistent with their data for other time-cycled devices. However, the extended range of the PneuPac HC, with a maximum flow capability of 180 litre min^{-1}, allows compensation for the decrement in performance over a range of chamber pressures at least up to 6 ATA. Beyond 6 ATA it is doubtful that this ventilator would meet the needs of most adult male patients.

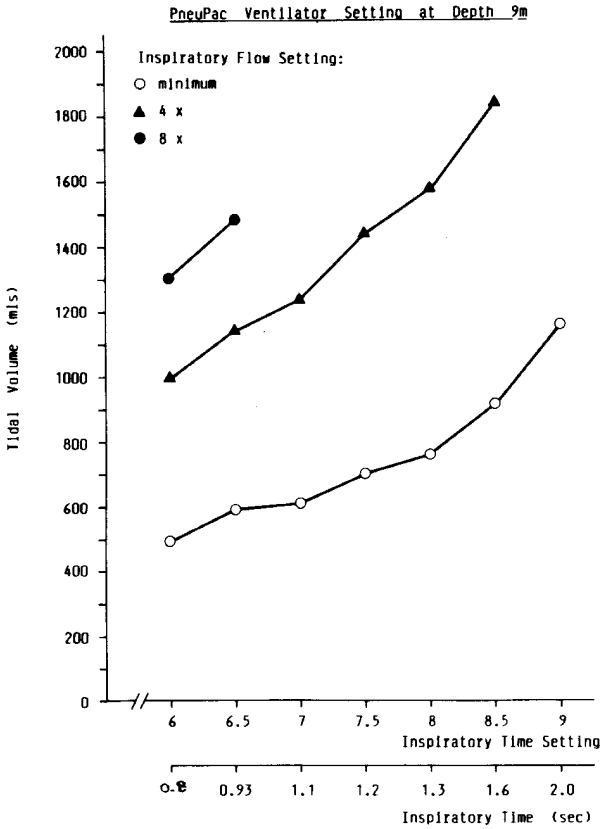

FIGURE 3. Tidal volumes generated at 1.9 Ata pressure at three different flow settings.

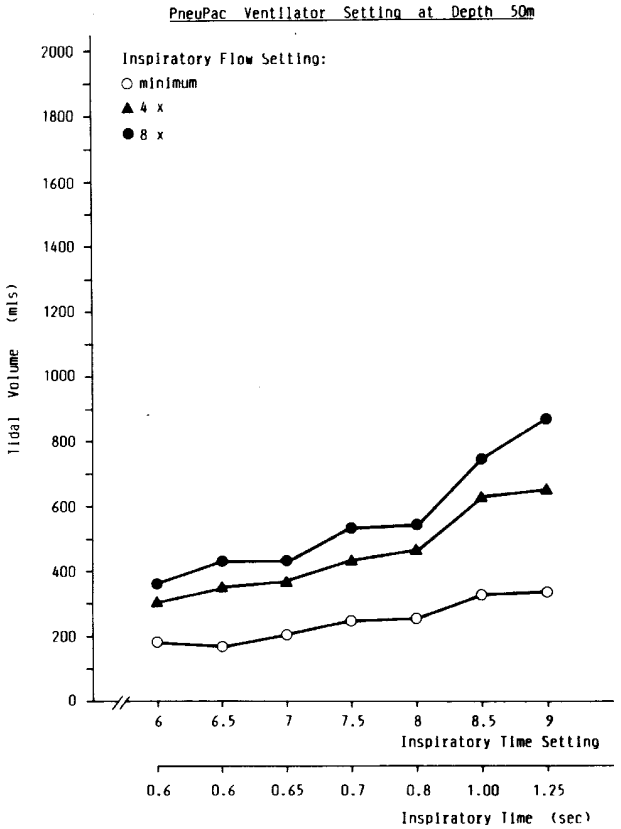

FIGURE 5. Tidal volumes generated at 6 Ata pressure at three different flow settings.

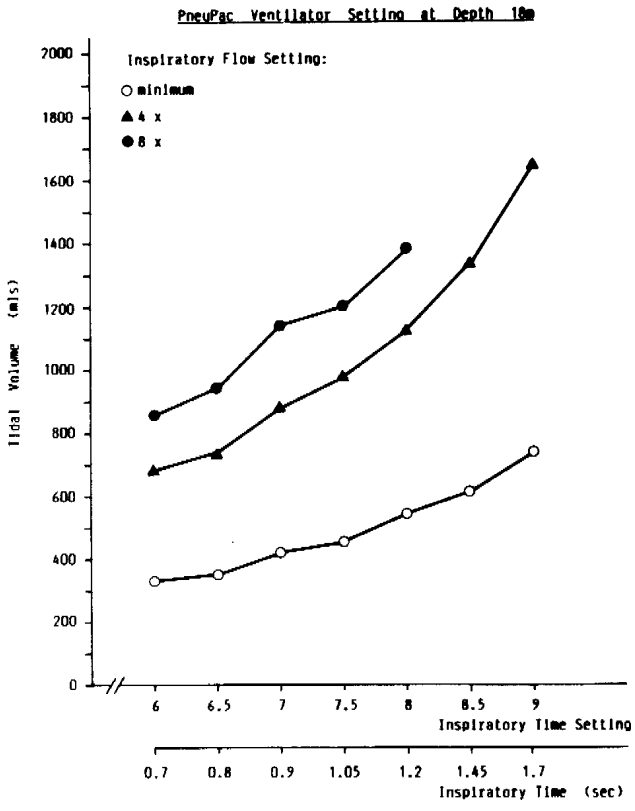

FIGURE 4. Tidal volumes generated at 2.8 Ata pressure at three different flow settings.

By making these recordings over the depth range customarily used for hyperbaric therapy, we have been able to construct a series of tables that allow us to choose appropriate settings on the ventilator to give the desired inspiratory time and tidal volume for any particular patient. The respiratory rate can then be adjusted by varying the expiratory time control, allowing setting of an appropriate breathing rate and minute volume. In addition tidal and minute ventilation should always be checked using some suitable device such as the Wright's Spirometer. The calibration errors for this device are small and likely to be of little importance in clinical use.

A limitation of the testing circuit used was that "lung" compliance which was roughly 30-40 ml/cm H_20^{-1} could not be altered. Whilst the design of the PneuPac HC ventilator as a flow generator is such that tidal volume should remain contant despite changes in patient compliance, we did not confirm this experimentally. In clinical use our impression has been that delivered tidal voume has not altered with changing compliance.

Two further factors influencing performance of ventilators are the driving gas pressure to the unit and the different densities of the delivered gases. In our chamber the delivered gas may be changed by turning a single valve.

TABLE 1
Calibration chart for clinical use at 6 Ata, showing tidal volumes for varying flow settings and inspiratory times. PneuPac Ventilator settings at 50 m depth (6 ATA)

Inspiratory Control Setting	**6**	**6.5**	**7**	**7.5**	**8**	**8.5**	**9**
Inspiratory Time in seconds	**0.6**	**0.6**	**0.65**	**0.70**	**0.80**	**1.00**	**1.25**
Flow control settings	**Delivered volume in millilitres**						
min	180	170	205	245	250	320	330
x1	195	210	235	265	280	345	385
x2	205	230	245	275	295	375	410
x3	250	280	300	340	375	480	515
x4	305	350	370	430	465	625	650
x5	325	390	400	480	490	670	700
x6	335	405	405	500	520	690	820
x7	345	420	420	510	530	720	845
x8	360	430	430	530	540	740	865
Max	425	-	-	-	-	-	-

Although our driving pressures for air and oxygen are slightly different, neither this nor the different densitites of the two gases altered the delivered tidal volumes at given settings to a degree that would be important clinically. Nevertheless it is important to consider these factors in setting up a mechanical ventilator in a recompression chamber. It is also important to ensure that the gas delivery systems can meet the maximal flow rates that any particular ventilator is capable of. Initial tests of the PneuPac HC in our facility quickly revealed that our oxygen delivery system was not capable of this and required modification.

The inspiratory and expiratory times of pneumatic time-cycled ventilators are well known to change with changes in ambient pressure, shortening as pressure increases. This is a serious limitation in the use of some ventilators. If gas density were the factor influencing this, then the converse would be expected to occur. Since cycling between inspiration and expiration is dependent in most such machines on the filling of a pressure cartridge as described above, Desautels and Blance[2] have proposed recently that this shortening of cycling time is due to the change in the compression factor of that compartment with changes in ambient pressure. Compressional gas losses are directly related to the volume of the container (in this case, the time cartridges) and inversely proportional to ambient pressure. This would result in less volume of gas being needed to flow into the cartridge to cycle it as ambient pressure increases. Our preliminary observations have been consistent with this hypothesis.

We have found the PneuPac HC ventilator to be a robust and consistent performer that can generate adequate tidal volumes within appropriate inspiratory times for the vast majority of adult patients, up to 6 ATA pressure. We would recommend manual ventilation of patients during all changes of chamber pressure, but we have found the PneuPac HC ventilator very suitable for clinical use during the prolonged treatments that critically ill patients may require.

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Drs A.J.Gibson, FFARACS, F.M.Davis, MD, FFARCS, and MsA.R.Wilkinson are members of the Hyperbaric Unit at the Princess Margaret Hospital, Christchurch, New Zealand.