Performance Comparison of 15 Transport Ventilators

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BACKGROUND: Numerous mechanical ventilators are designed and marketed for use in patient transport. The complexity of these ventilators differs considerably, but very few data exist to compare their operational capabilities. METHODS: Using bench and animal models, we studied 15 currently available transport ventilators with regard to their physical characteristics, gas consumption (duration of an E-size oxygen cylinder), battery life, ease of use, need for compressed gas, ability to deliver set ventilation parameters to a test lung under 3 test conditions, and ability to maintain ventilation and oxygenation in normal and lung-injured sheep. RESULTS: Most of the ventilators tested were relatively simple to operate and had clearly marked controls. Oxygen cylinder duration ranged from 30 min to 77 min. Battery life ranged from 70 min to 8 hours. All except 3 of the ventilators were capable of providing various F_{IO_2} values. Ten of the ventilators had high-pressure and patient-disconnect alarms. Only 6 of the ventilators were able to deliver all settings as specifically set on the ventilator during the bench evaluation. Only 4 of the ventilators were capable of maintaining ventilation, oxygenation, and hemodynamics in both the normal and the lung-injured sheep. CONCLUSIONS: Only 2 of the ventilators met all the trial targets in all the bench and animal tests. With many of the ventilators, certain of the set ventilation parameters were inaccurate (differed by > 10% from the values from a cardiopulmonary monitor). The physical characteristics and high gas consumption of some of these ventilators may render them less desirable for patient transport. *Key words: transport, mechanical ventilation, ventilator, positive end-expiratory pressure, PEEP, fraction of inspired oxygen, F_{IO_2}.* [Respir Care 2007;52(6): 740–751.

Introduction

Patients who require ventilatory support are frequently transported from one hospital location to another. Portable transport ventilators are also required in ambulances and in forward military positions. In addition, the threat of bioterrorism requires health care systems to be able and rapidly with very little notice to accept and ventilate large numbers of patients.

To provide ventilatory support under the above-defined conditions requires that transport ventilators be appropriately designed, though this does not mean they must be equivalent to intensive care unit ventilators.[1] Transport ventilators must incorporate certain characteristics to be of use in the above-defined settings.[1–3] First, they must be able to ventilate patients with healthy or acutely or chronically injured lungs. Second, they must be portable and easy to operate. Third, they must be able to deliver a high fraction of inspired oxygen (F_{IO_2}). Fourth, in forward military positions they must be able to operate on an internal battery for a long period, and without compressed gas.

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This study was partly funded by a grant from the United States Army, DAMD 17–02-2–0006.

Daniel W Chipman RRT presented a version of this report at the OPEN FORUM of 51st International Respiratory Congress of the American Association for Respiratory Care, held December 3–6, 2005, in San Antonio, Texas.

Conflict of interest: Robert M Kacmarek PhD RRT FAARC has received research grants and honoraria from Respironics, Maquet Medical, Tyco Puritan Bennett, and Hamilton Medical. Daniel W Chipman RRT is a paid consultant for and has received lecture honoraria from Maquet Medical.

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Table 1. Comparison of Evaluated Ventilators by Power Source, Physical Dimensions, Modes, F_{IO_2}, and PEEP

Ventilator	Approved as Transport Ventilator	Power Requirement	Size			Weight (kg)	Available Modes	F_{IO_2} (range or available values)	PEEP Available? (range cm H_2O)
			Height (cm)	Width (cm)	Depth (cm)				
Sophisticated									
Univent Eagle 754	Yes	Electricity	29	23	11	4.5	A/C, SIMV	0.21–1.0	Yes, 0–20
VersaMed iVent	Yes	Electricity	33	24	26	10	A/C (VP), SIMV (VP), PSV, CPAP	0.21–1.0	Yes, 0–20
Newport HT50	Yes	Electricity	26	27	20	6.8	A/C (VP), SIMV (VP), PSV, CPAP	0.21–1.0	Yes, 0–30
Pulmonetic Systems LTV 1000	Yes	Electricity	8	25	30	6.1	A/C (VP), SIMV (VP), PSV, CPAP	0.21–1.0	Yes, 0–30
Simple									
Oceanic Medical Products Magellan	Yes	Gas	12.7	17.8	10.2	2.1	CMV, IMV	1.0	No
Bio-Med Devices IC2A	Yes	Gas	26	16	9	4.1	A/C, SIMV	1.0	Yes, 0–30
Pneupac Parapac Medic	Yes	Gas	9.2	22	16.2	2.4	CMV, SIMV	0.5, 1.0	No
Pneupac Parapac Transport 200D	Yes	Gas	9.2	22	16.2	3.1	CMV, SIMV	0.5, 1.0	No
Life Support Products Auto Vent 2000	Yes	Gas	15	4.5	9	0.68	CMV	1.0	No
Carevent ATV+	Yes	Gas	23.5	11.1	16.2	4.1	CMV, IMV	0.6, 1.0	Yes, 0–20
Vortran RespirTech Pro	No	Gas	16.76	6.35	8.38	0.165	CMV, IMV	1.0	No
Percussionaire TXP	Yes	Gas	10.6	10.6	16.5	0.68	CMV, IMV	0.5	No
Bio-Med Devices Crossvent 3	Yes	Gas + electricity	22.9	28	12.7	4.32	A/C (VP), SIMV (VP), PSV, CPAP	0.5, 1.0	No
Bird Avian	Yes	Gas + electricity	25	30	12.7	4.5	A/C, SIMV	1.0	No
Pneupac Compac 200	Yes	Gas or electricity	36	21	21	8.5	CMV, IMV	0.45, 1.0	No

F_{IO_2} = fraction of inspired oxygen
PEEP = positive end-expiratory pressure
A/C = assist/control
SIMV = synchronized intermittent mandatory ventilation
VP = volume-controlled and pressure-controlled modes available
PSV = pressure support ventilation
CPAP = continuous positive airway pressure
CMV = controlled mechanical ventilation
IMV = intermittent mandatory ventilation

Fifth, they should be able to provide both assisted and controlled ventilation. Sixth, they must incorporate alarms that identify catastrophic conditions.

Previous evaluations of transport ventilators included only up to 8 ventilators.[4–10] Many of the ventilators previously evaluated have since been modified by the manufacturers, and new ventilators have entered the market. We present an evaluation of 15 transport ventilators for use during intrahospital or ambulance transport and in forward military positions. The goals of this study were (1) to determine if these transport ventilators could ventilate both healthy and injured lungs, and deliver tidal volumes (V_T) and respiratory rates (RR) as specifically set, and (2) to identify which ventilators would be most appropriate in which transport settings.

Methods

Table 1 shows power requirements, physical dimensions, available modes, available F_{IO_2} ranges and settings, and positive end-expiratory pressure (PEEP) range for the 15 tested ventilators. All 15 ventilators were provided by their respective manufacturers specifically for this evaluation. All 15 ventilators are approved by the U.S. Food and Drug Administration for use in transport, except the Vortran RespirTech Pro, which is marketed as a resuscitator.

Bench Protocol

We evaluated gas consumption, battery life, ease of use, physical characteristics, need for compressed gas, and the ability to deliver set ventilation parameters under 3 different test conditions. Gas consumption was defined as the amount of time the ventilator could function on one full E-size oxygen cylinder (capacity 660 L of oxygen), with the ventilator set to deliver a V_T of 1,000 mL at an RR of 10 breaths/min and an F_{IO_2} of 1.0. Battery life was defined as the amount of time the ventilator could function on a fully charged battery with the ventilator set to deliver a V_T of 1,000 mL at an RR of 10 breaths/min and an F_{IO_2} of 0.21.

A ventilator was considered easy to use if all the parameters were clearly labeled and easily set to deliver a precise variable (eg, V_T or RR). We assumed the manufacturer's published weight and dimensions to be accurate. Ability to ventilate without compressed gas was met if the ventilator could deliver the set minute volume ($\dot{V}_E$) under each of the test conditions without a compressed gas source or an external compressor.

The ability to deliver set parameters was evaluated with a test lung (Training and Test Lung, Michigan Instruments, Grand Rapids, Michigan) under 3 different test conditions: high resistance with normal compliance; normal resistance with normal compliance; and normal resistance with low compliance. High and normal resistance was achieved with resistors (Pneuflo Rp20 and Rp5, Michigan Instruments, Grand Rapids, Michigan). Normal and low compliance were set on the test lung (0.05 L/cm H_2O and 0.02 L/cm H_2O, respectively). For each condition the tested ventilator was set to deliver a V_T of 500 mL at 15 breaths/min and 30 breaths/min, and a V_T of 1 L at 10 breaths/min and 20 breaths/min.

V_T, RR, peak inspiratory pressure (PIP), and positive end-expiratory pressure (PEEP) were measured and analyzed with a cardiopulmonary monitor (NICO, Respironics, Wallingford, Connecticut) and its software (Analysis Plus, Respironics, Wallingford, Connecticut). Ventilator performance was determined by comparing the set parameters to the measurements from the cardiopulmonary monitor.

Each ventilator was bench tested as follows. With resistance set at 20 cm H_2O/L/s and compliance set at 0.05 L/cm H_2O, the ventilator was connected to the test lung, and the cardiopulmonary monitor's flow sensor was placed between the ventilator circuit and the flow resistor. V_T was initially set at 500 mL, RR at 15 breaths/min, inspiratory time (T_I) at 1.0 s (if setting the T_I was possible on that ventilator), and PEEP at 5 cm H_2O (if PEEP was available on the ventilator). The F_{IO_2} was set at the lowest available setting, which may have been 0.21, air mix (entrainment), or 1.0, depending on the ventilator's capabilities. Following a 10-breath stabilization period, we recorded PIP, mean airway pressure, PEEP, V_T, $\dot{V}_E$, RR, and the pressure, flow, and volume graphics. After that data collection, the RR was increased to 30 breaths/min and the T_I was decreased to 0.5 s. All other settings remained unchanged. Following another 10-breath stabilization period, we again recorded PIP, mean airway pressure, PEEP, V_T, $\dot{V}_E$, RR, and graphics. The V_T was then increased to 1,000 mL, RR was decreased to 10 breaths/min, and T_I was increased to 1 s. Following another stabilization period and data collection, the RR was increased to 20 breaths/min, and stabilization and data collection were repeated. All other settings remained unchanged. These settings were repeated for each of the compliance and resistance combinations. The cardiopulmonary monitor was interfaced with a laptop computer, on which the flow, volume, and pressure data were collected and analyzed. The set ventilation parameters, ventilator-displayed values, and cardiopulmonary-monitor-measured values were simultaneously recorded. All measurements during the bench assessment were at atmospheric-temperature-and-pressure-dry conditions.

Laboratory Protocol

This protocol was approved by the animal care committee of Massachusetts General Hospital, Boston, Massachusetts.

Using 30-kg sheep, we evaluated each ventilator's ability to ventilate both healthy and saline-lavage lung-injured sheep. In both settings we evaluated the ventilator's ability to maintain normal arterial blood gas values and cardiopulmonary hemodynamics. We studied 12 sheep: 6 with normal lungs and 6 with saline-lavage lung injury. Five ventilators were evaluated on each sheep (healthy and injured), and each group of 5 ventilators was studied on 2 healthy and 2 injured sheep. Three groups of 5 ventilators were randomly selected.

Healthy Lung Evaluation

Each group of ventilators was randomly applied for a 60-min period to a healthy sheep. Initially, each ventilator was set at a V_T of 9 mL/kg and an RR of 20 breaths/min, with a T_I or peak flow setting to maintain a T_I of 1.0 s. If the device was capable of applying PEEP, PEEP of 5 cm H_2O was applied with 50% oxygen. The ventilator was attached to the animal's airway, followed by a 15-min stabilization period. After stabilization we collected arterial and mixed venous blood samples, and measured systemic arterial pressure, pulmonary artery pressure, pulmonary capillary wedge pressure, and heart rate. Airway pressure and V_T were measured at the endotracheal tube (ETT). Cardiac output was measured in triplicate, using the thermodilution technique. The ventilator was adjusted and oxygen added if needed to attempt to reach the target blood gas values (P_{aO_2} 60–100 mm Hg, P_{aCO_2} 30–50 mm Hg, pH 7.30–7.50). Once we determined whether the targets could be met, the next ventilator was attached to the animal's airway for evaluation.

Injured Lung Evaluation

During the lung-injury tests, the ventilator was initially set at a V_T of 6 mL/kg, an RR of 30 breaths/min, PEEP of 15 cm H_2O (if available), and F_{IO_2} of 0.50. Again, blood gases and hemodynamics were evaluated to determine if the target blood gas values (P_{aO_2} 60–100 mm Hg, P_{aCO_2} 30–50 mm Hg, pH 7.30–7.50) had been met, then the ventilator was adjusted as necessary to attempt to meet the targets. Once we determined whether the targets could be met, the next ventilator was attached to the animal's airway for evaluation.

Instrumentation

We used 12 female Dorset sheep (21–31 kg), each fasted for 24 hours. Orotracheal intubation, with an 8-mm inner-diameter ETT, was performed during deep halothane anesthesia via mask. The external jugular vein was then cannulated, and an 8 French sheath introducer was inserted. After line placement, the anesthesia delivery was changed to intravenous only, with a loading dose of 10 mg/kg pentobarbital, 4 mg/kg ketamine, and 0.1 mg/kg pancuronium, followed by continuous infusion of pentobarbital (4 mg/kg/h), ketamine (8 mg/kg/h), and pancuronium (0.1 mg/kg/h) to provide surgical anesthesia with paralysis. After intubation, the basic ventilatory settings were volume control ventilation at a V_T of 10 mL/kg, inspiratory-expiratory ratio of 1:2, F_{IO_2} of 1.0, and PEEP of 5 cm H_2O, delivered by an intensive care ventilator (840, Puritan Bennett, Carlsbad, California). RR was adjusted to achieve eucapnia (P_{aCO_2} 35–45 cm H_2O).

An 18-gauge catheter was then placed into the carotid artery for continuous measurement of arterial blood pressure and sampling of arterial blood gas values. Arterial and mixed venous blood samples were drawn for blood gas analysis. P_{O_2}, P_{CO_2}, pH, oxyhemoglobin saturation, and hemoglobin content were assessed with a blood gas analyzer (282, Ciba Corning Diagnostics, Norwood, Massachusetts). Flow at the ETT was measured by a heated pneumotachometer (Hans Rudolph, Kansas City, Missouri) connected to a differential pressure transducer (MP-45 ± 2 cm H_2O, Validyne, Northridge, California). Volume was determined via digital integration of the flow signal. A differential pressure transducer (MP-46 ± 100 cm H_2O, Validyne, Northridge, California) was used to measure airway opening pressure. Cardiac output and pulmonary arterial pressure were measured via a 7.5 French pulmonary artery catheter (831 HF 7.5, Edwards Life Sciences, Irvine, California) inserted into the left external jugular vein. Proper position of the catheter was confirmed via pressure waveform analysis before and after balloon occlusion. Following instrumentation and a 30-min stabilization period, 5 transport ventilators were randomly applied.

All signals (flow at the ETT, airway opening pressure, arterial blood pressure, and pulmonary arterial pressure) were amplified (8805C, Hewlett Packard, Waltham, Massachusetts), converted to digital signals with an analog-to-digital converter (DI-220, Dataq Instruments, Akron, Ohio), and recorded at a sampling rate of 100 Hz, with data-acquisition software (Windaq/200, version 1.36, Dataq Instruments, Akron, Ohio). Ventilatory measurements made during the animal tests were all made at body-temperature-and-pressure-saturated conditions. All infusions, including the anesthetic, were given via volumetric infusion pump. A heating blanket was used to maintain a core temperature of 38–39°C. An orogastric tube was placed to empty the stomach.

Lung Injury

Severe lung injury was produced with bilateral lung lavage via instillations of 1 L of isotonic saline, warmed to 39°C, repeated every 30 min, until P_{aO_2} decreased to $\leq$ 100 mm Hg at an F_{IO_2} of 1.0 and a PEEP of 5 cm H_2O. A stable lung injury was defined as a P_{aO_2} change of $<$ 10% after 60 min. It took 2–4 lavages and 2–3 hours to establish a stable lung injury. During development and stabilization of lung injury, the animals were ventilated with the Puritan Bennett 840 ventilator. After a stable lung injury was established, 5 transport ventilators were randomly applied.

On completion of the protocol, the animals were sacrificed under deep anesthesia (10 mg/kg pentobarbital) with rapid infusion of 50 mL saturated potassium chloride solution. Electrocardiogram and arterial blood pressure readings confirmed cardiac standstill.

Statistical Analysis

Formal statistical analysis was not performed. Lung model data were compared to the ventilator settings. A difference $>$ 10% was considered excessive, because most of the ventilator manufacturers indicate that the normal range of operation is within 10% of the set parameters. The mean ± SD V_T was calculated from 5 breaths.

PIP, PEEP, and RR did not change with any ventilator during the bench evaluation. During the normal and injured-lung animal evaluations, the ability of each ventilator to achieve the target blood gas values was evaluated. The oxygen cylinder duration and battery life were recorded in minutes.

Results

Bench Test

The 15 ventilators evaluated can be classified as either "simple" or "sophisticated" transport ventilators, and as those that require compressed gas (pneumatic), those that can operate without compressed gas but require electrical power, and those that require both or either power source. The data in the tables and figures are organized with that

Table 2. Operational Features of Evaluated Ventilators: Battery, Gas Consumption, Alarms, and Ease of Use

Ventilator	Battery Powered	Battery Life*	External Gas Required	Oxygen Cylinder Duration (min)†	Disconnect Alarm	High-Pressure Alarm	Able to Ventilate Normal Lungs	Able to Ventilate Injured Lungs	Ease of Use‡
Sophisticated									
Univent Eagle 754	Yes	4 h	No	35	Yes	Yes	Yes	No	1
VersaMed iVent	Yes	90 min	No	52	Yes	Yes	Yes	Yes	1
Newport HT50	Yes	8 h, 10 min	No	46	Yes	Yes	Yes	Yes	1
Pulmonetic Systems LTV 1000	Yes	75 min	No	32	Yes	Yes	Yes	No	1
Simple									
Oceanic Medical Products Magellan	No	NA	Yes	60	Yes	Yes	Yes	No	1
Bio-Med Devices IC2A	No	NA	Yes	30	No	No	Yes	Yes	2
Pneupac Parapac Medic	No	NA	Yes	68§	Yes	Yes	Yes	No	1
Pneupac Parapac Transport 200D	No	NA	Yes	62	Yes	Yes	Yes	No	1
Life Support Products AutoVent 2000	No	NA	Yes	60	No	No	Yes	No	1
Carevent ATV+	No	NA	Yes	65	Yes	Yes	Yes	No	1
Vortran RespirTech Pro‖	No	NA	Yes	Variable	No	No	No	No	3
Percussionaire TXP‖	No	NA	Yes	77¶	No	No	Yes	Yes	3
Bio-Med Devices Crossvent 3**	Yes	NA	Yes	53	No	No	Yes	No	1
Bird Avian**	Yes	NA	Yes	30	Yes	Yes	Yes	No	1
Pneupac Compac 200	Yes	4 h	No	65	Yes	Yes	Yes	No	2

*Battery life is based on tidal volume (V_T) of 1 L, respiratory rate of 10 breath/min, and fraction of inspired oxygen (F_{IO_2}) of 0.21.

†The oxygen cylinder duration is the time it took to consume 1 full E-size oxygen cylinder with the ventilator set at V_T of 1 L, respiratory rate of 10 breaths/min, and F_{IO_2} of 1.0

‡Ease of use: 1 = clearly labeled and easy to access; 2 = clearly labeled but difficult to access; 3 = not clearly labeled and difficult to access.

§V_T gradually decreased as cylinder became depleted to 200 mL just before the ventilator shut down.

‖True pressure-cycled ventilator. Changes in resistance or compliance significantly altered the delivered V_T. Difficult to set at desired parameters.

¶F_{IO_2} fixed at 0.5.

**Pneumatically powered, electronically controlled ventilator. Battery and/or alternating current electricity are required for electronic controls, monitoring, etc. Compressed gas is required for ventilation.

NA = not applicable

schema. Five of the ventilators tested can be classified as sophisticated transport ventilators; the other ten are simple transport ventilators.

Eight of the ventilators were purely pneumatic (they rely completely on compressed gas and do not require any other power source). Most of these incorporate an air-entrainment device to provide different F_{IO_2} values. The Oceanic Medical Products Magellan and the Life Support Products AutoVent 2000 are the exceptions; all breaths are delivered with 100% source gas. Four ventilators were capable of ventilating with only battery or alternating-current power. Oxygen was not required, but may be added to increase F_{IO_2}.

The third group consisted of the 3 ventilators that require both compressed gas and electricity (battery or alternating current). These ventilators incorporate a pneumatic gas-delivery system and also require battery or alternating current to operate their electronic controls.

Table 1 shows the ventilators' physical dimensions and ventilation modes. There are considerable differences in the size and weight. In some ventilators the modes are very limited, whereas others have multiple pressure and volume modes.

Gas consumption (Table 2) ranged from 30 min to 77 min. Battery life ranged from 75 min to 8 hours and 10 min. All except 5 ventilators (Bio-Med Devices IC2A, Bio-Med Devices Crossvent 3, Life Support Products AutoVent 2000, Percussionaire TXP, and Vortran RespirTech Pro) incorporated both a low-pressure/disconnect alarm and a high-inspiratory-pressure alarm.

One interesting finding was with the Bio-Med Devices Crossvent 3. When changing from the "Air Mix" setting to 100% oxygen, the delivered V_T approximately doubled above the set V_T. According to the manufacturer, this is expected, and the operations manual instructs to adjust the flow accordingly.

The Percussionaire TXP was the most difficult to operate, and its controls were not clearly identified. The Bio-Med Devices IC2 and the Oceanic Medical Products Magellan were the only ventilators operable near a magnetic resonance imaging device.

Tables 3 and 4 show the bench performance data. Most of the ventilators performed at or close to specifications under bench test conditions. The measured V_T of most of the ventilators was less than the set V_T, and this discrepancy increased under conditions of increased resistance or decreased compliance. Seventy-eight individual tests were performed at a V_T of 1,000 mL. In 32 of these tests the

Table 3. Bench Performance at a Tidal Volume of 500 mL

	High Resistance and Normal Compliance				Normal Resistance and Normal Compliance				Normal Resistance and Low Compliance			
	V_T (mean ± SD mL)	RR (br/min)	PIP (cm H_2O)	PEEP (cm H_2O)	V_T (mean ± SD mL)	RR (br/min)	PIP (cm H_2O)	PEEP (cm H_2O)	V_T (mean ± SD mL)	RR (br/min)	PIP (cm H_2O)	PEEP (cm H_2O)
Sophisticated Transport Ventilators												
Univent Eagle 754*	554 ± 3.1†	15	19	5	583 ± 4.5†	15	12	5	571 ± 8.4†	15	32	5
Univent Eagle 754‡	535 ± 2.9	29	31	5	570 ± 5.1†	30	16	5	555 ± 3.6†	29	34	5
VersaMed iVent*	557 ± 3.2†	15	19	4	541 ± 11.5	15	12	5	515 ± 16.3	15	32	4
VersaMed iVent‡	401 ± 7.1†	30	25	4	555 ± 25.2†	30	16	4	496 ± 6.1	30	32	5
Newport HT50*	480 ± 9.2	15	18	4	477 ± 12.1	15	14	4	498 ± 4.5	15	29	5
Newport HT50‡	468 ± 4.8	29	21	9	459 ± 7.4	30	14	5	494 ± 6.7	30	30	4
Pulmonetic Systems LTV 1000*	483 ± 3.5	15	16	5	486 ± 2.0	15	14	5	476 ± 3.5	15	29	5
Pulmonetic Systems LTV 1000‡	483 ± 4.2	30	20	7	484 ± 3.8	30	16	6	477 ± 1.3	30	29	5
Simple Transport Ventilators												
Oceanic Medical Products Magellan*	411 ± 1.3†	23†	16	5	462 ± 2.9	21†	11	5	441 ± 10.4†	21†	26	4
Oceanic Medical Products Magellan‡	428 ± 3.1†	30	26	5	410 ± 0.9†	31	12	5	418 ± 1.6†	32	27	5
Bio-Med Devices IC2A*	487 ± 0.6	17†	17	6	487 ± 0.8	17†	13	6	474 ± 1.5	18†	31	6
Bio-Med Devices IC2A‡	483 ± 1.7	30	31	7	519 ± 1.8	30	16	6	487 ± 3.1	30	32	6
Pneupac Parapac Medic*	507 ± 1.0	15	17	5	530 ± 1.2	15	16	6	483 ± 2.9	16	28	5
Pneupac Parapac Medic‡	306 ± 0.9†	30	14	6	324 ± 1.0†	30	13	6	312 ± 2.6†	30	20	5
Pneupac Parapac Transport 200D*	472 ± 1.6	16	18	5	485 ± 1.8	16	14	5	462 ± 10.2	16	27	4
Pneupac Parapac Transport 200D‡	456 ± 1.5	30	20	7	479 ± 0.8	30	15	6	461 ± 11.7	30	27	5
Life Support Products AutoVent 2000*	475 ± 1.1	15	13	NA	504 ± 2.7	15	12	NA	445 ± 7.5†	15	23	NA
Life Support Products AutoVent 2000‡	472 ± 5.5	17†	12	NA	497 ± 5.3	18†	12	NA	438 ± 9.8†	18†	24	NA
Carevent ATV+*	535 ± 1.3	13†	16	5	560 ± 3.1†	12†	15	5	549 ± 2.0	12†	31	6
Carevent ATV+‡	555 ± 5.1†	25†	24	5	570 ± 3.8†	25†	16	5	575 ± 10.7†	25†	34	6
Vortran RespirTech Pro	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Percussionaire TXP	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

(Continued)

Table 3. (Continued)

	High Resistance and Normal Compliance				Normal Resistance and Normal Compliance				Normal Resistance and Low Compliance			
	V_T (mean ± SD mL)	RR (br/min)	PIP (cm H_2O)	PEEP (cm H_2O)	V_T (mean ± SD mL)	RR (br/min)	PIP (cm H_2O)	PEEP (cm H_2O)	V_T (mean ± SD mL)	RR (br/min)	PIP (cm H_2O)	PEEP (cm H_2O)
Bio-Med Devices Crossvent 3*	526 ± 2.0	15	20	5	532 ± 0.9	15	16	5	507 ± 1.1	15	30	5
Bio-Med Devices Crossvent 3‡	507 ± 1.5	30	25	8	523 ± 0.8	30	18	9	520 ± 1.1	30	31	5
Bird Avian*	472 ± 0.6	15	15	6	467 ± 3.2	15	13	7	475 ± 1.3	15	29	6
Bird Avian‡	473 ± 1.6	30	29	7	489 ± 2.7	30	16	10	488 ± 2.9	30	32	6
Pneupac Compac 200*	410 ± 4.0†	15	14	6	429 ± 5.8†	14	13	5	390 ± 8.7†	14	23	4
Pneupac Compac 200‡	436 ± 5.0†	29	20	6	442 ± 5.8†	29	15	6	424 ± 6.9†	29	26	5

*Respiratory rate set at 15 breaths/min

†Measured value was > 10% different from the setting on the ventilator

‡Respiratory rate set at 30 breaths/min

V_T = tidal volume. RR = respiratory rate. br/min = breaths/min. PIP = peak inspiratory pressure. PEEP = positive end-expiratory pressure. NA = not applicable.

measured V_T was >10% different than the set V_T, and in 19 of these tests the measured RR was >10% different than the set RR.

Seventy-eight individual tests were performed at a V_T of 500 mL. In 28 of these tests the measured V_T was >10% different than set V_T, and in 15 of these tests the RR was >10% different than the set RR. The inability to meet the target V_T is partially explained by compressible volume loss, since none of these units compensates for the volume loss due to compression. The compressible volume was 0.91 ± 0.39 mL/cm H_2O (range 0.43–1.65 mL/cm H_2O), and since the PIP values were at most in the mid-30s, only about one third of the volume loss can be attributed to compressible volume. Two of the ventilators (Vortran RespirTech Pro and Percussionaire TXP) were not included in the bench test because their design was incompatible with our protocol; they did not incorporate readily identifiable parameter settings.

Three of the ventilators were unable to meet some of the test conditions, due to their designs. The Carevent ATV+ achieves V_T by setting $\dot{V}_E$ and RR, with a maximum $\dot{V}_E$ of 14 L/min and an inspiratory-expiratory ratio of 1:2 to establish T_I. The Pneupac Compac 200 also achieves V_T by setting $\dot{V}_E$ and RR with a maximum $\dot{V}_E$ of 14 L/min. The Life Support Products AutoVent 2000 has 2 controls: V_T and RR, with a maximum RR of 17–18 breaths/min. Inspiratory time and flow vary with changes in $\dot{V}_E$. At high RR settings the inspiratory-expiratory ratio is >1:1.

Animal Evaluations

We evaluated 14 ventilators with healthy and saline-lavage-injured sheep. We were unable to evaluate the Vortran RespirTech Pro in either animal model because the weight of the sheep (20–31 kg) was below the operating range of this ventilator (minimum 40 kg). All of the 14 ventilators tested were capable of ventilating the healthy lungs (Fig. 1). Ventilators without F_{IO_2} control met the pH and P_{aCO_2} targets, but exceeded the P_{aO_2} target. With all the ventilators, hemodynamics were stable throughout the tests.

Four ventilators (VersaMed iVent, Newport HT50, Bio-Med Devices IC2A, and Percussionaire TXP) met all the targets when ventilating injured lungs (Fig. 2). Seven ventilators (Pulmonetic Systems LTV 1000, Bird Avian, Oceanic Medical Products Magellan, Pneupac Parapac Transport 200D, Pneupac Parapac Medic, Bio-Med Devices Crossvent 3, and Carevent ATV+) successfully ventilated the lungs of only one of the 2 lung-injured animals. The remaining 3 ventilators (Univent Eagle 754, Pneupac Compac 200, and Life Support Products AutoVent 2000) failed to meet the ventilation targets in either of the 2 lung-injured sheep used. In all cases of failure, the P_{aCO_2} and/or pH targets were not met. In most cases, the RR setting was the limiting parameter. All 14 ventilators met the oxygen-

Table 4. Bench Performance at a Tidal Volume of 1,000 mL

	High Resistance and Normal Compliance				Normal Resistance and Normal Compliance				Normal Resistance and Low Compliance			
	V_TM (mean ± SD mL)	RR (br/min)	PIP (cm H_2O)	PEEP (cm H_2O)	V_T (mean ± SD mL)	RR (br/min)	PIP (cm H_2O)	PEEP (cm H_2O)	V_T (mean ± SD mL)	RR (br/min)	PIP (cm H_2O)	PEEP (cm H_2O)
Sophisticated Transport Ventilators												
Univent Eagle 754*	1,028 ± 4.7	10	36	5	1,102 ± 3.1†	10	22	5	1,055 ± 4.7	10	56	5
Univent Eagle 754‡	1,027 ± 2.8	20	35	5	1,097 ± 6.8	20	22	5	1,009 ± 5.7	20	55	5
VersaMed iVent*	989 ± 74.9	10	33	5	996 ± 58.8	10	20	5	906 ± 17.3	10	51	5
VersaMed iVent‡	932 ± 6.3	20	40	5	972 ± 66.6	20	20	4	929 ± 0.8	20	51	5
Newport HT50*	926 ± 8.9	10	36	4	940 ± 24.9	10	23	3	962 ± 20.2	10	52	5
Newport HT50‡	920 ± 14.8	20	37	5	944 ± 14.4	20	24	4	967 ± 15.4	20	54	5
Pulmonetic Systems LTV 1000*	955 ± 1.1	10	36	5	945 ± 6.7	10	24	5	927 ± 10.8	10	52	5
Pulmonetic Systems LTV 1000‡	954 ± 2.5	20	37	6	949 ± 1.7	20	24	5	926 ± 2.1	20	52	5
Simple Transport Ventilators												
Oceanic Medical Products Magellan*	789 ± 2.2†	12†	29	5	752 ± 1.6†	12†	16	4	753 ± 6.1†	12†	42	4
Oceanic Medical Products Magellan‡	870 ± 3.3†	24†	34	6	842 ± 4.2†	25†	17	5	850 ± 7.6†	25†	47	5
Bio-Med Devices IC2A*	910 ± 1.7	9	35	6	952 ± 2.1	10	20	6	898 ± 4.4†	10	52	6
Bio-Med Devices IC2A‡	887 ± 1.2†	21	37	7	937 ± 1.1	21	20	6	886 ± 4.1†	21	52	6
Pneupac Parapac Medic*	942 ± 2.9	11	28	5	973 ± 3.5	11	24	6	899 ± 6.5†	10	53	5
Pneupac Parapac Medic‡	635 ± 2.0	20	24	5	653 ± 2.2†	20	19	6	614 ± 4.6†	20	36	5
Pneupac Parapac Transport 200D*	784 ± 2.7†	12†	27	5	840 ± 1.7†	12†	21	4	750 ± 15.5†	12†	41	4
Pneupac Parapac Transport 200D‡	774 ± 1.6†	21	28	6	835 ± 2.4†	21	21	5	755 ± 3.2†	22†	42	5
Life Support Products AutoVent 2000*	925 ± 1.5	10	23	NA	948 ± 4.7	10	20	NA	892 ± 2.6†	10	44	NA
Life Support Products AutoVent 2000‡	913 ± 4.8	17†	22	NA	939 ± 5.4	17†	20	NA	896 ± 4.1†	17†	44	NA
Carevent ATV+*	1,132 ± 1.9†	9	28	5	1,164 ± 1.3†	9	25	5	1,125 ± 5.2†	9	56	6
Carevent ATV+‡	1,142 ± 1.3†	13†	33	5	1,179 ± 5.2†	13†	26	5	1,149 ± 1.4†	13†	58	5
Vortran RespirTech Pro	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Percussionaire TXP	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Bio-Med Devices Crossvent 3*	975 ± 0.7	10	38	4	1,016 ± 1.7	10	25	5	948 ± 1.1	10	51	5
Bio-Med Devices Crossvent 3‡	972 ± 0.9	20	39	5	1,017 ± 0.8	20	25	4	953 ± 9.7	20	51	4
Bird Avian*	950 ± 2.6	10	33	6	970 ± 3.1	10	20	6	958 ± 4.7	10	52	5
Bird Avian‡	947 ± 2.7	20	35	8	972 ± 3.1	20	21	7	958 ± 4.0	20	53	6
Pneupac Compac 200*	917 ± 1.3	9	24	6	917 ± 9.8	9	21	5	794 ± 13.6†	9	42	4
Pneupac Compac 200‡	654 ± 6.0†	18†	23	6	654 ± 7.3†	18†	15	5	629 ± 12.2†	18†	36	4

*Respiratory rate set at 15 breaths/min

†Measured value was > 10% different from the setting on the ventilator

‡Respiratory rate set at 30 breaths/min

V_T = tidal volume. RR = respiratory rate. br/min = breaths/min. PIP = peak inspiratory pressure. PEEP = positive end-expiratory pressure. NA = not applicable.

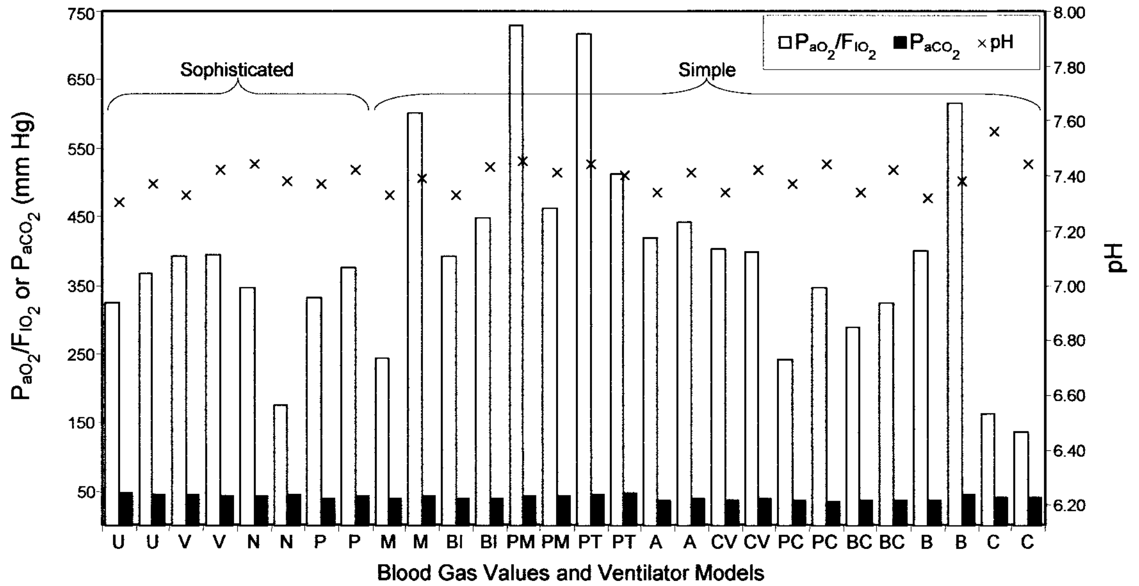

Fig. 1. P_{aCO_2}, arterial pH, and ratio of P_{aO_2} to fraction of inspired oxygen (F_{IO_2}) in healthy (no lung injury) sheep during ventilation with 14 transport ventilator models. Each set of values represents data from a single sheep. Assessment was performed on 2 sheep with each ventilator. The large variability in the ratio of P_{aO_2} to fraction of inspired oxygen (P_{aO_2}/F_{IO_2}) is because some of the ventilators only offer only 1 or 2 F_{IO_2} settings, and because of the level of gas exchange in each sheep. The Vortran RespirTech Pro could not be used on the animals we tested. The Percussionaire TXP and the Vortran RespirTech Pro could not be set to the specifications required by the lung model. U = Univent Eagle 754. P = Pulmonetic Systems LTV 1000. V = VersaMed iVent. B = Bird Avian. M = Oceanic Medical Products Magellan. N = Newport HT50. PT = Pneupac Parapac Transport 200D. PM = Pneupac Parapac Medic. C = Pneupac Compac 200. BI = Bio-Med Devices IC2A. BC = Bio-Med Devices Crossvent 3. CV = Carevent ATV+. A = Life Support Products AutoVent 2000. PC = Percussionaire TXP.

ation target under all conditions with the lung-injured sheep. As with the uninjured sheep, with all the ventilators the hemodynamics were stable throughout the tests.

Discussion

The major findings of this study are:

1. All the evaluated ventilators were able to maintain normal ventilation and hemodynamics in healthy sheep.
2. In the lung-injured sheep, few of the ventilators could be set to meet the P_{aCO_2} or pH targets. The ventilators unable to meet these targets were limited by the RR setting.
3. In the bench study, only 6 of the ventilators met the V_T and RR settings under all the test conditions.
4. Only 5 of the ventilators (Univent Eagle 754, VersaMed iVent, Newport HT50, Pulmonetic Systems LTV 1000, and Pneupac Compac 200) can operate without a compressed gas source, and their battery life differed considerably.
5. A full E-size cylinder of oxygen allowed ventilation with 100% oxygen for only 30–77 min.
6. The 2 ventilators most suitable for use in front-line rescue situations, where oxygen may not be available, are the Newport HT50 and the Univent Eagle 754.

Use of Transport Ventilators

Transport ventilators are required in various settings: intra-hospital, inter-hospital, pre-hospital, and in the field by military or civilian authorities.[3] Each of these settings has different priorities regarding ventilator design. In forward military or field use by civilian groups, the ideal ventilator would be simple to operate, battery powered, compact, lightweight, and would operate without compressed gas. In that setting it is unlikely that the patient will be breathing spontaneously, so versatility of available modes is unnecessary. Similar issues exist during pre-hospital transport, but compressed gas is readily available in most ambulances, so a pneumatically operated ventilator is as acceptable as a battery operated unit. During inter-hospital transport the patient may be breathing spontaneously, which necessitates patient-triggered ventilation, and frequently these patients require high F_{IO_2}.

The most common use of transport ventilators is in intra-hospital transport. At Massachusetts General Hospital, the respiratory care department performs about 30 one-way patient transports per day and another 10–15 are performed by the anesthesia department, all of which require continuous mechanical ventilation. Most of these trans-

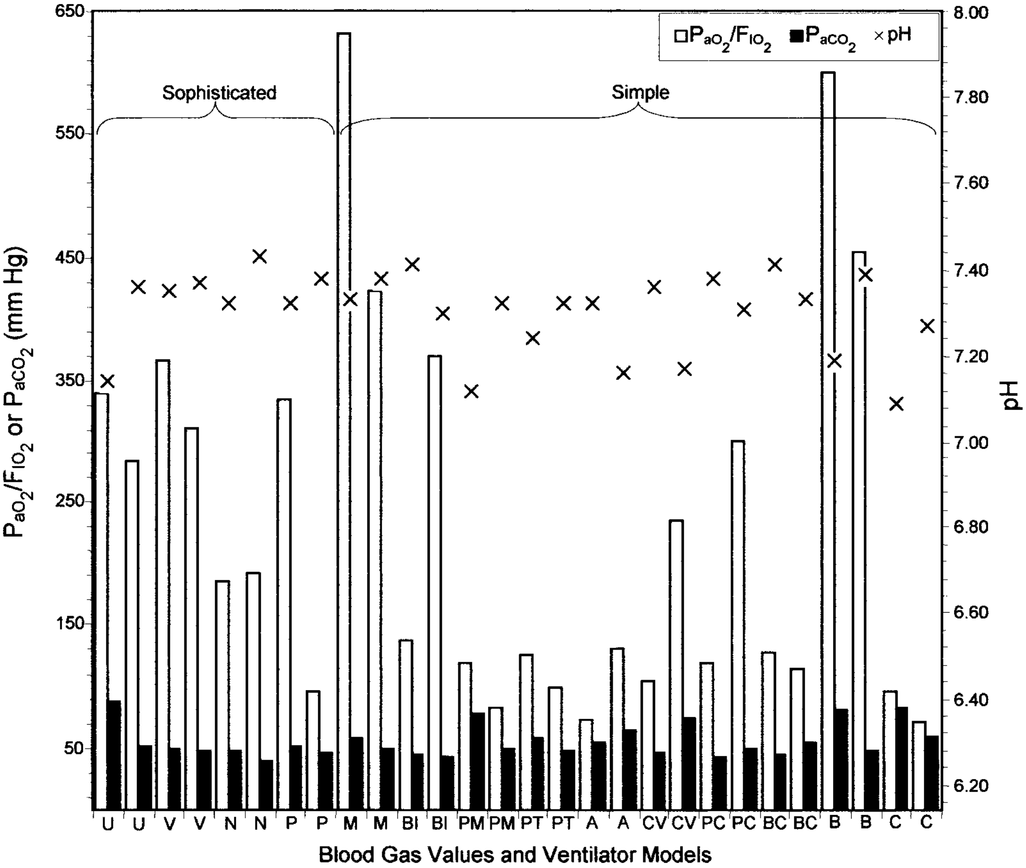

Fig. 2. P_{aCO_2}, arterial pH, and ratio of P_{aO_2} to fraction of inspired oxygen (F_{IO_2}) in lung-injured sheep during ventilation with 14 transport ventilator models. Each set of values represents data from a single sheep. Assessment was performed on 2 sheep with each ventilator. The large variability in the ratio of P_{aO_2} to fraction of inspired oxygen (P_{aO_2}/F_{IO_2}) is because some of the ventilators only offer 1 or 2 F_{IO_2} settings, and because of the level of gas exchange in each sheep. The Vortran RespirTech Pro could not be used on the animals we tested. The Percussionaire TXP and the Vortran RespirTech Pro could not be set to the specifications required by the lung model. U = Univent Eagle 754. P = Pulmonetic Systems LTV 1000. V = VersaMed iVent. B = Bird Avian. M = Oceanic Medical Products Magellan. N = Newport HT50. PT = Pneupac Parapac Transport 200D. PM = Pneupac Parapac Medic. C = Pneupac Compac 200. BI = Bio-Med Devices IC2A. BC = Bio-Med Devices Crossvent 3. CV = Carevent ATV+. A = Life Support Products AutoVent 2000. PC = Percussionaire TXP.

ports are to and from diagnostic areas, the operating room, or the emergency department.

It is well documented that transport ventilators provide more stable gas exchange and hemodynamics than manual ventilators.[10–13] Gervais et al[11] observed severe respiratory alkalosis during transport with manual ventilation. In 20 patients transported to diagnostic areas, Braman et al[12] found substantial respiratory acidosis or alkalosis and hemodynamic compromise in 16 patients receiving manual ventilation. Hurst et al[13] also documented respiratory alkalosis during intrahospital transport of 28 patients receiving manual ventilation. Nakamura et al[10] also observed greater variability of gas exchange and hemodynamics during transport with manual ventilation than with a transport ventilator.

Types of Transport Ventilators

Austin et al[3] classified transport ventilators into 3 categories, based on their capabilities: automatic resuscitators, simple transport ventilators, and sophisticated transport ventilators. They defined a simple transport ventilator as one that provides a specified rate and volume with a high-pressure relief valve,[3] whereas a sophisticated transport ventilator has modes that allow spontaneous breathing, and additional alarms and monitors of gas delivery. Five of the ventilators we evaluated were sophisticated: Newport HT50, Univent Eagle 754, VersaMed iVent, Pulmonetic Systems LTV 1000, Bird Avian.

We considered the Newport HT50 and the Univent Eagle 754 most suited for use in forward military positions, because they have longer battery life (8 hours and 4 hours, respectively). The VersaMed iVent was the heaviest of the units evaluated (10 kg). However, the Newport HT50, Univent Eagle 754, VersaMed iVent, and Pulmonetic Systems LTV 1000 clearly could function exceptionally well in all transport settings if they had longer battery life. The Bird Avian was the most limited in this regard, because it lacks a battery and needs compressed gas to operate.

Issues/Problems With Specific Ventilators

The choice of a ventilator is also determined by other specific design issues. Only 2 of the ventilators (Bio-Med Devices IC2 and Oceanic Medical Products Magellan) are designed for use during magnetic resonance imaging. The following ventilators had no alarms: Vortran RespirTech Pro, Bio-Med Devices IC2, Percussionaire TXP, Oceanic Medical Products Magellan, and Life Support Products AutoVent 2000.

Many of the ventilators allow very few F_{IO_2} values: Vortran RespirTech Pro (F_{IO_2} 1.0), Bio-Med Devices IC2 (F_{IO_2} 1.0), Oceanic Medical Products Magellan 2000 (F_{IO_2} 1.0), Pneupac Parapac Transport 200D (F_{IO_2} 0.5 or 1.0), Pneupac Parapac Medic (F_{IO_2} 0.5 or 1.0), Bio-Med Devices Crossvent 3 (F_{IO_2} 0.5 or 1.0), Carevent ATV+ (F_{IO_2} 0.8 or 1.0), and Life Support Products AutoVent 2000 (F_{IO_2} 1.0).

The oxygen cylinder life of the Pneupac Parapac Medic exceeded the maximum estimated time (66 min), because V_T gradually decreased as the cylinder became depleted to 200 mL just before the ventilator shut down.

With the Percussionaire TXP, the maximum F_{IO_2} delivered was 0.5, which accounts for its 77-min cylinder life. Note, however, that the volume of gas in E-size cylinders does vary, because filling pressure varies, which adds to the variability in cylinder life.

With the Newport HT50 and its nondisposable proprietary circuit, intrinsic PEEP developed at higher RR because of high expiratory resistance. With the Bio-Med Devices IC2, Life Support Products Magellan 2000, Pneupac Parapac Transport 200D, and Pneupac Parapac Medic the V_T is set with the flow rate and T_I controls, and RR is controlled by those two plus an expiratory time control. With the Carevent ATV+, V_T is determined by $\dot{V}_E$ and RR. The Life Support Products AutoVent 2000 has 2 controls (RR and V_T), its maximum RR is 18 breaths/min, and it does not have any alarms. The Pneupac Compac 200 is designed for military use. It has a sturdy case, and V_T is adjusted by setting $\dot{V}_E$ and RR. It has a fixed T_I of 1 s and a maximum RR of 26 breaths/min. The Percussionaire TXP is a pressure-limited and time-cycled ventilator, and its V_T varied with changes in impedance, but we found that even with constant impedance the V_T drifted upwards.

The maximum RR with the Life Support Products AutoVent 2000 is 18 breaths/min, and with the Carevent ATV+ it is 40 breaths/min. With the Oceanic Medical Products Magellan, setting RR at 15 breaths/min and 20 breaths/min resulted in measured RR of 23 breaths/min and 30 breaths/min, respectively.

The most difficult ventilator to evaluate was the Vortran RespirTech Pro. This ventilator has few clearly labeled controls, and the manufacturer's specified patient-weight range was outside the weight range of the animals we used. However, it is the smallest and lightest of the ventilators we tested, and it is only for single-patient use.

It may be necessary with some of these ventilators to monitor gas delivery with a secondary monitor because of the large difference between the set and actual V_T and RR. Since we did not assess these ventilators during spontaneous breathing, we cannot comment on patient-ventilator synchrony or the difference between the set and delivered parameters during spontaneous ventilation.

Comparison With Other Studies

Nolan et al[5] evaluated the performance of 6 pneumatically operated ventilators. Similar to our results, they noted that the overall ability of the ventilators they tested to maintain delivered V_T, $\dot{V}_E$, and RR consistent with the set levels diminished as resistance increased or compliance decreased. McGough et al[6] observed the same problem with 8 pneumatically operated ventilators they evaluated with a test lung. The Univent 750 was evaluated by Campbell et al,[7] with a test lung, during controlled and patient-triggered ventilation. They observed, as we did, that with the Univent Eagle 754, gas delivery was not markedly affected by a decrease in compliance or an increase in resistance.

More recently, Miyoshi et al[8] evaluated 4 ventilators with transport capabilities, all with internal batteries. However, at least 3 of these units (Puritan Bennett 740, Bird T-Bird, and Respironics Espirit) would not be considered typical transport ventilators. However, all of these units, along with the Pulmonetic Systems LTV 1000, were capable of ventilating a test lung during assisted ventilation, at various ventilation settings.

Zanetta et al[9] evaluated 5 transport ventilators and 3 intensive care unit ventilators during controlled and patient-triggered ventilation with a test lung. They determined that V_T varied $< 10\%$ as delivered V_T varied from 300 mL to 800 mL and compliance and resistance were varied. However, they noted that, because of high resistance to exhalation, all the portable ventilators they evaluated trapped gas at high $\dot{V}_E$.

Limitations

The primary limitation of the present study is that it was not performed with patients. However, the bench and animal evaluations did simulate common settings required by patients during controlled ventilation. In addition, the animal model evaluations were consistent with pediatric patients, not adults. This limited the assessment of some of the ventilators. We also did not evaluate any of these ventilators during spontaneous breathing, which is clearly a major issue in transport within and between hospitals. As a result, we cannot comment on their performance during spontaneous triggering. Also, we evaluated only one ventilator from each company, and we cannot be sure that the single ventilator we tested reflects the operation of all ventilators of that model.

Conclusions

Only 2 of the transport ventilators evaluated met the trial targets in all bench and animal settings. With some ventilators the settings were inaccurate. The physical characteristics and high gas consumption of some of these ventilators may render them less desirable for patient transport.

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