Pressures Available for Transtracheal Jet Ventilation from Anesthesia Machines and Wall-Mounted Oxygen Flowmeters

Jens Fassl, MD

Uta Jenny, MD

Sergei Nikiforov, MD

W. Bosseau Murray, MB, ChB

Patrick A. Foster, MD

BACKGROUND: Oxygen supplies capable of supporting transtracheal jet ventilators can be lifesaving. There is not much information about which oxygen sources (readily available inside and outside operating rooms) have sufficient driving pressure for transtracheal jet ventilation.
METHODS: We measured driving pressures (upstream or residual oxygen pressure) in a specially designed jet ventilation test system with a 2.25-mm (14-gauge) IV catheter. High-pressure oxygen sources evaluated included wall-mounted (Puritan, Allied Health, Precision, and Datex-Ohmeda) and anesthesia machine auxiliary oxygen flowmeters and oxygen flush valves from anesthesia machines (Draeger Narkomed 2B, Narkomed 4, Datex-Ohmeda Excel, and Datex-Ohmeda Modulus).
RESULTS: All 4 types of wall-mounted oxygen flowmeters, opened past their highest scale settings (15 L/min), delivered sufficient working pressures (range, 103–282 kPa; 16–41 psi). Working pressures from auxiliary oxygen flowmeters mounted on Datex-Ohmeda machines were adequate to support jet ventilation (range, 189–248 kPa; 27–36 psi), whereas those on tested Draeger machines did not supply sufficient pressure for jet ventilation: Narkomed 2B, 14–28 kPa (2–4 psi); Narkomed 4, 24–28 kPa (3–4 psi). Working pressures delivered by oxygen flush valves on tested Draeger machines were adequate to support jet ventilation, ranging from 96 to 117 kPa (14–17 psi), whereas pressures generated by tested Datex-Ohmeda flush valves were not (ranging from 50 to 62 kPa, 7–9 psi).
CONCLUSION: Oxygen sources other than dedicated jet ventilator connectors to high-pressure pipeline oxygen may supply adequate working pressure, but each type of oxygen source needs testing to ensure that it supplies adequate working pressure.
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During emergency management of patients with difficult airways, the availability and use of jet ventilation through a transtracheal catheter can be lifesaving.[1,2] The inability to provide life-sustaining gas exchange under circumstances in which neither ventilation by mask nor intubation can be achieved has been responsible for up to 30% of deaths attributed to anesthesia.[3–5] Currently available commercial jet ventilators require a connection to a high-pressure oxygen supply, for instance, on some anesthesia machines in which connectors are readily available. Thus, a jet ventilator and personnel instructed in its use will often not be available when airway emergencies in patients with unexpected difficult airways occur outside the operating room (OR). We therefore investigated the utility of wall-mounted oxygen flowmeters as a source of oxygen pressure for jet ventilation compared with oxygen flush valves found on anesthesia machines, which have been shown to be satisfactory.[6]

The static oxygen pipeline pressure* provided in hospitals in the United States is about 378 kPa (55 psi).[7] During use for jet ventilation, this pressure will decrease. The pressure of interest is the residual or working pressure† available for jet ventilation through a 2.25-mm (14-gauge) IV catheter. This is the actual pressure driving oxygen through the 2.25-mm (14-gauge) catheter into the patient, for which we use the term "working pressure." Commercially available jet ventilators include pressure regulators specifically designed to reduce the dangerously high pipeline pressure to safer but effective levels. Although pressure must be reduced

From the Simulation Development and Cognitive Science Laboratory, Pennsylvania State University College of Medicine, Hershey, Pennsylvania.

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Address correspondence and reprint requests to W. Bosseau Murray, MB, ChB, Simulation Development and Cognitive Science Laboratory, Pennsylvania State University College of Medicine, 500 University Ave., Hershey, PA 17033. Address e-mail to wmurray1@hmc.psu.edu.

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*Static oxygen pipeline pressure refers to the pipeline pressure while no oxygen is flowing.

†Residual pressure (or working pressure) refers to upstream driving pressure remaining while oxygen is flowing through the 14-gauge cannula. We accepted, based on the literature, a minimum working pressure of 103 kPa (15 psi) as the minimum pressure required to drive the jet ventilator (see Discussion).

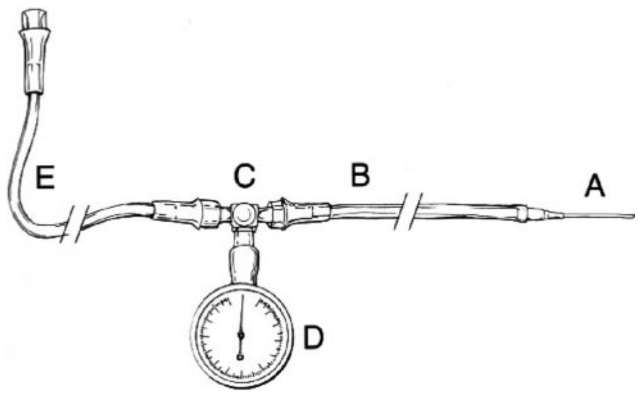

Figure 1. The specially designed, constant flow test assembly used to measure the "working pressure" (driving pressure while jet ventilator is fully open to atmosphere). A, 2.25-mm (14-gauge) IV catheter; B and E, airline oxygen tubing; C, Hi-Flo 3-Way Stopcock; D, oil-filled pressure gauge.

to reduce the chance of injury, the working pressure should be at least 103 kPa (15 psi) to drive sufficient oxygen through a 14-gauge IV catheter.

The purpose of this study was to measure the pressures available for jet ventilation from the oxygen sources with anesthesia machines and from several types of wall-mounted oxygen outlets, as found in the postanesthesia care unit, emergency room, surgical intensive care unit (SICU), medical intensive care unit, and the general wards in a typical hospital. A complete list of the working pressures available to drive oxygen through a 2.25-mm (14-gauge) IV catheter from these sources has not been published. We examined which oxygen sources could be used with a 2.25-mm (14-gauge) catheter for transtracheal jet ventilation.

METHODS

The measurement technique called for a test system to provide a constant flow of oxygen through a 2.25-mm (14-gauge) catheter rather than the standard jet ventilation devices that are designed for intermittent flow. The measurement technique also had to consider the decrease in available pipeline pressure caused by the flow of oxygen; as soon as flow occurs, the supply pressure decreases to a new, lower level ("working pressure"), which represents the balance between the inflow and outflow. On the basis of the literature, we accepted 103 kPa (15 psi) as the minimum pressure required for jet ventilation.

Therefore, to enable measurement of the working pressures during continuous use of the test jet ventilator system, we assembled equipment in the following sequence (test assembly) for our measurements (Fig. 1):

1. 2.25-mm (14-gauge) 56.7-mm Jelco™ IV catheter (4068, 0294G84, Critikon, 1748C, Tampa, FL)
2. 2.1-m Airline Oxygen tubing, vinyl-tipped (Lot No. YOCO262, Cat. 001301, Allegiance, McGaw Park, IL)
3. Hi-Flo 3-Way Stopcock (24D22076, MX 931-IL, Medex, Hilliard, OH)
4. 2.1-m Airline Oxygen tubing (as in item 2)
5. Standard 7-mm endotracheal tube connector (Intermediate Hi-Lo, Cat. #86450, Lot M041150, MMJ S.A. de C.V., Mexico, G.P. 32580) to connect test system to the common gas outlet of the anesthesia machine. The tubing (as in item 4) connected directly to the wall-mounted oxygen flowmeters (without the need for a coupling piece)
6. Connecting tubing connected to third opening of 3-Way Stopcock (as in item 3, 5-mm internal diameter; 20-cm length)
7. Oil-filled pressure gauge with a range of 0 to 413 kPa (0–60 psi) connected to 7 (WIKA, Lawrenceville, GA)

We connected the test assembly in turn to each of the following oxygen sources:

1. Anesthesia machines:
   a. Datex-Ohmeda Modulus and Datex-Ohmeda Excel (Datex-Ohmeda, The BOC Group, Madison, WI)
   b. Narkomed 2B and Narkomed 4 (North American Draeger, Telford, PA)
      i. to the common gas outlet of each anesthesia machine
      ii. to the auxiliary oxygen flowmeter of each anesthesia machine
2. Wall-mounted oxygen flowmeters:
   a. Allied Health (TL 015 Model, Allied Health Instrument Corp., St. Louis, MO)
   b. Precision (IMFA 1001, Precision Medical, Northampton, PA)
   c. Datex-Ohmeda (AHE, BOC Health Care, Columbia, MD)
   d. Puritan (Series B, no manufacturer details available).

We first determined the influence of 6 identical (from the same manufacturer) 2.25-mm (14-gauge) IV catheters on the working pressures from a single source (Datex-Ohmeda wall-mounted oxygen flowmeter) during jet ventilation to check for variability. Because the variability of the pressures was only minimal and not clinically relevant when using different catheters of the same size, we continued the testing with a single 2.25-mm (14-gauge) IV catheter.

The following anesthesia machines were used for our measurements: Narkomed 2B, Narkomed 4, Datex-Ohmeda Modulus, and Datex-Ohmeda Excel. These machines were in different locations (main OR, labor and delivery OR, outpatient OR, and spare machines) and tested on different days. The machine type, serial number, service date, vaporizer, and further available information were documented. The oxygen pipeline pressures for the different locations and days were documented before and during the measurements.

We connected the test equipment to the common gas outlet of the anesthesia machine and pressed and held the emergency oxygen button on the anesthesia machine. We read the pressure on the pressure gauge. Air could be heard and felt escaping between the body of the vaporizer and the rotating head of the Draeger anesthesia machines. We examined each vaporizer to determine which vaporizer "leaked." Every measurement was repeated 5 times. All available anesthesia machines in our institution were studied using the above protocol.

Four different types of wall-mounted oxygen flowmeters (Datex-Ohmeda, Allied Health, Puritan, and Precision) at different locations (pediatric and adult postanesthesia care unit, surgical intensive care unit, trauma bay, emergency room, and floor) at the Hershey Medical Center were tested on different days. Flowmeter manufacturers, types, and serial numbers were noted where available. The oxygen pipeline pressures for the different locations and days were documented before and during the experiments. The oxygen pipelines were all parts of the clinical hospital system and maintained as per standard regulations.

We also tested the auxiliary oxygen flowmeters mounted on the anesthesia machines. The flow ranges of the flowmeters were 0–10 L/min for the Draeger anesthesia machines and 0–15 L/min for the Datex-Ohmeda anesthesia machines. The steps of the pressure measurements for the oxygen flowmeters mounted on the anesthesia machines and the wall were made as follows:

1. Wall pressure (oxygen supply pressure) was noted (with no oxygen flowing).
2. Flowmeter was opened to obtain its highest flow setting according to the calibrated scale (10 or 15 L/min), with no back pressure (i.e., jet ventilator not connected).
3. Test measurement system was connected.
4. Pressure reading on the oil-filled pressure gauge of the test assembly was noted.
5. New (lower) reading on the oxygen flowmeter (L/min) was noted (but not reported).
6. Flowmeter was opened further, past the highest flowmeter scale setting.[7] All the flowmeters had a definite, clear "stop," past which it was not possible to open the device any further.
7. Pressure reading on the oil-filled pressure gauge was noted while the oxygen was flowing through the 2.25-mm (14-gauge) IV catheter (this is the working pressure, as defined previously).
8. Because the flowmeter bobbin was past (higher than) the highest setting on the scale, no flow reading could be obtained on the auxiliary oxygen flowmeter.
9. Wall pressure ("working pressure") was noted during the flow of oxygen.

Every pressure measurement was repeated 5 times for each flowmeter. Six different flowmeters of each brand were tested. The means, standard deviations, and ranges were calculated for each individual flowmeter. The averages of each of the 6 different flowmeters were used to calculate (and report) the mean and standard deviations for each group of flowmeters. Pressures were measured in psi and converted to kPa using a conversion factor of 0.145.

Commercial Jet ventilators

Using a similar methodology, we tested 3 commercially available jet ventilators (AINCA, Anesthesia Associates, San Marcos, CA, Cat. #00-325):

As a baseline measurement, we measured the working pressures with the commercial devices connected in the conventional format directly to a high-pressure oxygen source.

As a comparative measurement, we measured the working pressures provided to the commercial devices by each of the wall-mounted oxygen flowmeters mentioned above.

The serial numbers of all tested devices are provided in the Appendix.

RESULTS

Variability Because of IV Catheters

When using 6 different 2.25-mm (14-gauge) IV catheters with the highest scale setting on the flowmeter, the working pressures measured during jet ventilation were 28 kPa (4 psi) with minimal variation. The working pressure for a totally open setting (maximum possible flow setting with the flowmeter opened wider than the highest calibrated/rated setting) was 234 kPa (34 psi), also with minimal variation. Because the measurements for the highest scale setting and for the totally open setting showed only minimal variability, we considered the differences between catheters to be not clinically relevant.

Anesthesia Machine Common Gas Outlet (Oxygen Flush Valve)

All tested machines were in current use and serviced within the previous 3 months as per clinical requirements. We tested 15 Narkomed 2B machines, 3 Narkomed 4 machines, 3 Datex-Ohmeda Modulus machines, and 1 Datex-Ohmeda Excel machine. The pipeline oxygen pressures varied between 372 and 392 kPa (54–57 psi) during our measurements. The pressure measurements obtained from the oxygen flush valves ranged from 96 to 117 kPa (14–17 psi) with a mean of 102 kPa (14.8 psi) for the Narkomed 2B machines; from 96 to 103 kPa (14–15 psi) with a mean of 99 kPa (14.3 psi) for the Narkomed 4 machines; from 50 to 55 kPa (7.2–8 psi) for the Datex-Ohmeda Modulus machines with a mean of 52 kPa (7.6 psi); and all 5 readings were 62 kPa (9 psi) for the Datex-Ohmeda Excel machine (Table 1).

Table 1. Working Pressures Obtained with Different Anesthesia Machines Using the Oxygen Flush Valve as the Source of High-Pressure Oxygen Flow

Anesthesia machine	*N*	Static wall pressure in kPa (mean ± SD)	Working pressure in kPa (mean ± SD)
Narkomed 2B	15	376 ± 11	102 ± 66
Narkomed 4	3	372	99 ± 4
Datex Ohmeda Modulus	3	386 ± 6	52 ± 7
Datex Ohmeda Excel	1	372	62

N is the number of each type of anesthesia machine tested. Static wall pressure in kPa is the pressure read on the anesthesia machine pressure gauge without any oxygen flow. Working pressure is the pressure measured upstream of the 2.25-mm (14 gauge) IV catheter, connected to the anesthesia machine circuit while using the oxygen flush valve. Mean is the average pressure.

Table 2. Working Pressures Obtained with Auxiliary Flow Meters of Different Anesthesia Machines

Auxiliary flowmeter type	*N*	Wall pressure in kPa (mean ± SD)	Working pressure in kPa (mean ± SD)
Narkomed 2B	15		
HSS		374 ± 9	19 ± 5
TOS			27 ± 5
Narkomed 4	3		
HSS		372	14 ± 2
TOS			25 ± 2
Datex Ohmeda Modulus	3		
HSS		377 ± 4	33 ± 5
TOS			239 ± 8
Datex Ohmeda Excel	1		
HSS		392	34
TOS		392	190

N is the total number of anesthesia machines tested, wall pressure in kPa is the pressure read on the anesthesia machine pressure gauge without any oxygen flow, and the working pressure is the pressure measured upstream to the 2.25-mm (14 gauge) IV catheter, connected to the anesthesia machine flowmeter. HSS is with the control valve open to allow oxygen flow (L/min) set to the flowmeter's maximum number in L/min on its scale (10 L/min for Draeger machines, 15 L/ min for Datex Ohmeda machines) and TOS maximum is with the control valve open completely, allowing maximum possible oxygen flow through the flowmeter.
HSS = highest scale setting; TOS = totally open setting.

Table 3. Working Pressures Measured from Different Wall-Mounted Oxygen Flow Meters

Type of wall-mounted oxygen flowmeter	*N*	Wall pressure in kPa (mean ± SD)	Working pressure in kPa (mean ± SD)
Puritan	6		
HSS		383 ± 6	29 ± 4
TOS			147 ± 41
Timeter	6		
HSS		381 ± 3	34 ± 2
TOS			267 ± 6
Precision	6		
HSS		379	29 ± 2
TOS			252 ± 21
Ohmeda	6		
HSS		383 ± 6	30 ± 4
TOS			257 ± 11

N is the total number of flowmeters tested, wall pressure in kPa is the pressure read on the anesthesia machine pressure gauge without any oxygen flow. The working pressure is the pressure measured upstream to the 2.25-mm (14 gauge) intravenous catheter, connected to the anesthesia machine flowmeter. HSS is with the control valve open to allow oxygen flow (L/min) set to the flowmeter rated highest number in L/min on its scale (15 L/min for wall-mounted oxygen flowmeters). TOS is with the control valve open completely, allowing maximum possible oxygen flow through the flowmeter.
HSS = highest scale setting; TOS = totally open setting.

With the Draeger anesthesia machines, we noted that with the use of the oxygen flush valve, gas escaped from underneath the head of the vaporizer even though the vaporizer was closed. There was no consistent pattern in which vaporizers leaked: the first, second, or last in sequence; most recently used or opened; or type of vaporizer (halothane, enflurane, isoflurane, or sevoflurane). Despite the audible leak, the residual working pressures were still sufficient (i.e., >103 kPa; Table 1.) As expected (based on the design), at no stage did any of the desflurane vaporizers leak. None of the Datex-Ohmeda anesthesia machines had a leak from the vaporizer during activation of the oxygen flush button.

Anesthesia Machine Auxiliary Flowmeters

The working pressures obtained from the auxiliary flowmeters on the Narkomed anesthesia machines (15 of Narkomed 2B and 3 of Narkomed 4) varied from 14 to 28 kPa (2–4 psi) while set at the highest scale flow (10 L/min). This working pressure did not increase sufficiently (i.e., remained significantly <103 kPa), even when set on the maximum possible flows (Table 2).

The working pressures, measured with the auxiliary oxygen flowmeters on the 3 Datex-Ohmeda Modulus anesthesia machines, varied from 28 to 38 kPa (4–5.5 psi) at the highest flow according to the flowmeter scales (15 L/min) and ranged from 231 to 248 kPa (33.5–36 psi) (Table 2) while set on the maximum possible flow.

The 5 working pressures, measured with the oxygen flowmeter on the single Datex-Ohmeda Excel anesthesia machine, all read 34 kPa (5 psi) at the highest flow according to the flowmeter scales (15 L/min) and ranged from 189 to 193 kPa (27.5–28 psi) (Table 2).

Wall-Mounted Oxygen Flowmeters

The working pressure measurements obtained from the wall-mounted oxygen flowmeters varied from 24 to 34 kPa (3.5–5 psi) at the highest flow setting of the flowmeters (15 L/min) and ranged from 100 to 282 kPa (14.5–41 psi) while set at the maximum possible flow (Table 3). The working pressures (measured at maximum possible flow) tended to be the lowest (but still sufficient) with the Puritan flowmeters. The Puritan flowmeter pressures varied from 100

Table 4. Working Pressures Measured from 3 Commercially Available Jet Ventilators with Auxiliary Flowmeter from Draeger Anesthesia Machine 6400 and Different Wall-Mounted Oxygen Flowmeters

Type of device	Wall pressure in kPa (mean)	Working pressure in kPa (mean ± SD)
Draeger anesthesia machine 6400	372	
Auxiliary flowmeter		
HSS		5 ± 7
TOS		7 ± 6
Oxygen flush valve		2 ± 3
Puritan		
HSS	324	28 ± 14
TOS		120 ± 38
Timeter		
HSS	326	28 ± 21
TOS		179 ± 50
Precision		
HSS	324	21 ± 12
TOS		168 ± 51
Ohmeda		
HSS	323	30 ± 21
TOS		184 ± 49

Three commercially available jet ventilators (AINCA, Anesthesia Associates, San Marcos, CA) were tested. Wall pressure in kPa is the pressure read on the control or anesthesia machine pressure gauge without any oxygen flow. The working pressure is the pressure measured upstream to the 2.25-mm (14 gauge) IV catheter, connected to the analogue pressure gauge on the jet ventilator. The mean is the average working pressure. HSS is with the control valve open to allow oxygen flow (L/min) set to the flowmeter rated highest number in L/min on its scale (15 L/min for wall-mounted oxygen flowmeters). TOS is with the control valve open completely, allowing maximum possible oxygen flow through the flowmeter.

HSS = highest scale setting; TOS = totally open setting.

to 172 kPa (14.5–25 psi) with a mean of 147 kPa (21.3 psi) (Table 3).

Commercially Available Jet Ventilators

The "static" wall oxygen pressures (i.e., without oxygen flow) obtained from the control panel, and the pressure gauge from the anesthesia machine, varied from 323 to 372 kPa (47–54 psi). The working pressures provided by a conventional high-pressure oxygen source, directly connected to the commercial jet ventilator, varied from 179 to 283 kPa (26–41 psi). The working pressures for the wall-mounted oxygen flowmeters were all sufficient (i.e., >103 kPa), whereas the working pressures for the Draeger anesthesia machine's auxiliary flowmeter were insufficient (Table 4).

DISCUSSION

Because jet ventilation is not needed very often, it is not economical or feasible to have dedicated oxygen outlets for commercial jet ventilators at every location where jet ventilation might be required. Although there can be life-threatening complications with jet ventilation,[8,9] it can, however, be lifesaving during attempts to establish an adequate airway.[10,11]

We were interested in determining whether jet ventilation could be used outside the OR environment and whether sufficient working pressures could be obtained using equipment readily available outside the OR, such as oxygen flowmeters. Furthermore, we tested whether the anesthesia machines available in our clinical environment could act as a "high-pressure oxygen source" at sufficiently high pressures to drive a jet ventilator. We defined a high-pressure oxygen source as a pressure in the range of wall (pipeline) supply pressure and above. We also compared our results with published data.

Oxygen Flush Valves

Published literature on working pressures necessary for transtracheal jet ventilation systems suggest that the oxygen flush valves of some anesthesia machines supply sufficient working pressure for jet ventilation.[3] Gaughan et al.[6] studied the Draeger Narkomed 2, 2A, 2B, and 3 anesthesia machines, as well as the Datex-Ohmeda Modulus II, Modulus II Plus, and the Datex-Ohmeda Modulus CD anesthesia machines. They concluded that the working pressures of the Draeger Narkomed 2A, 2B, and 3 anesthesia machines, as well as of the Datex-Ohmeda Modulus II Plus and the Datex-Ohmeda Modulus CD anesthesia machines, supplied sufficient pressure (124 kPa or 18 psi) to give adequate tidal volumes for jet ventilation in model lungs. However, according to their study, the Draeger Narkomed 2 and the Datex-Ohmeda Modulus II did not supply adequate working pressures from the oxygen flush valve. Bould and Bearfield[12] measured the flow achieved through a transtracheal catheter and compared their device ("construction") to a Manujet jet ventilator and to a Sanders injector for emergency ventilation. This "construction" (as they termed their homemade device) consisted of a standard hospital wall oxygen supply, flowmeter, oxygen tubing, and a 3-way tap. They found that this system was appropriate for emergency use in the absence of a jet ventilator.

Zornow et al.[13] performed an animal study using 3 different systems for jet ventilation. They were able to document sufficient ventilation and oxygenation using a jet ventilator attached to the oxygen pipeline and the flush valve of the anesthesia machine. Histological examinations of the tracheas, after using 345-kPa (50-psi) sources for the jet ventilation, demonstrated tracheal injuries, and they concluded that lower pressures of 103–206 kPa (15–30 psi), as used by Lawler et al.,[14] may minimize these injuries. On the basis of these studies, we considered working pressures of approximately 103 kPa or more (15 psi) as sufficient for jet ventilation. Where we had comparable measurements, the working pressures observed during our measurements using the oxygen flush valve on anesthesia machines were consistent with the data obtained by Gaughan et al.[6] Therefore, our measurements now expand this database: we consider the working pressures produced by the Narkomed 4 as sufficient and the Datex-Ohmeda Excel flush valve pressures as insufficient for jet ventilation (Table 1).

The idea for this study originated when, during training sessions for simulated airway emergencies in the Simulation Development and Cognitive Science Laboratory of the Pennsylvania State University College of Medicine, we noted that oxygen flowmeters could produce much higher flows than the maximum flow rate printed on the flow scale. This is evident when opening auxiliary flowmeters to the maximum scale setting and then continuing to open the control valves. This observation led us to evaluate the pressures available for jet ventilation, at such higher flows, using the auxiliary oxygen flowmeters of anesthesia machines as well as wall-mounted oxygen flowmeters at other hospital locations. We must explicitly indicate that the use of oxygen flowmeters (wall-mounted or on anesthesia machines) above their stated upper limit is not approved by the Food and Drug Administration or supported by the manufacturers.

Auxiliary Oxygen Flowmeters

During tests using the auxiliary oxygen flowmeters on all the types of anesthesia machines (at the highest scale setting on the flowmeter scale), no anesthesia machine generated sufficient working pressure to drive a jet ventilator. The working pressures varied from 14 to 38 kPa (2–5.5 psi). For instance, the working pressures generated by both types of Draeger anesthesia machine flowmeters at the maximum rated flow (control valve opened to the maximum allowable/calibrated flow) varied between 24 and 28 kPa (3.5–4 psi). These pressures are insufficient working pressures for jet ventilation.

Opening the auxiliary oxygen flowmeter beyond the maximum scale setting had different results for the 2 makes of anesthesia machines:

- The working pressures provided by the auxiliary oxygen flowmeter on the Draeger machines were still insufficient to drive a jet ventilator.
- The working pressures generated by the Datex-Ohmeda machines at the totally open setting (opened beyond the maximum scale setting) varied between 189 and 248 kPa (27–36 psi), which is adequate for jet ventilation.

The Narkomed 2B and Narkomed 4 anesthesia machines are equipped with auxiliary oxygen flowmeters with the highest rated flow at 10 L/min. The oxygen supply for the Draeger machines' auxiliary oxygen flowmeter passes through the plumbing of the anesthesia machine. The Datex-Ohmeda machines are provided with "external" oxygen flowmeters, which are fed directly from the oxygen pipeline. The auxiliary oxygen flowmeters of the Datex-Ohmeda machines are therefore similar to the wall-mounted oxygen flowmeters in terms of a "direct" oxygen supply and also have the highest oxygen flow rate of 15 L/min on the scale. It is not clear to us whether the different rated flows (10 L/min vs 15 L/min on the auxiliary oxygen flowmeters of the anesthesia machines) are sufficient to explain the differences in working pressures during jet ventilation.

Wall-Mounted Oxygen Flowmeters

At the highest scale setting, none of the wall-mounted oxygen flowmeters provided sufficient working pressure for jet ventilation, as the pressure varied from 24 to 38 kPa (3.5–5 psi), where 103 kPa (15 psi) is considered the minimum working pressure for jet ventilation. At the totally open setting, all wall-mounted oxygen flowmeters provided sufficient working pressure. We considered the lowest measured working pressure of 100 kPa (14.5 psi) of the Puritan flowmeter sufficiently close to 103 kPa (15 psi) to be considered adequate.

Commercially Available Jet Ventilation System

We compared the results from our test setup with a commercially available jet ventilation system. The range of working pressures with a commercially available jet ventilator connected in the conventional fashion directly to a wall oxygen source of 372 kPa (54 psi) varied from 179 to 283 kPa (26–41 psi) (Table 4), which is similar to the results from our test system. Similar to our test system, none of the wall-mounted oxygen flowmeters at the highest scale setting provided sufficient pressure to drive a jet ventilator. Similar to the results from our test system, the totally open setting on the wall-mounted oxygen flowmeters supplied sufficient working pressure, i.e., >103 kPa (15 psi). Similar to our results, the auxiliary oxygen flowmeter on the Draeger anesthesia machine did not provide sufficient pressure.§ Given the similarities of results, we therefore conclude that our test device adequately represents a commercially available jet ventilation system.

The strength of the study is that we included all the anesthesia machines and tested several wall-mounted oxygen outlets at different locations, which are in use in a Level I Trauma Center. Bould and Bearfield[12] presented a similar study in 2008 in which the oxygen flowmeter was opened beyond the highest scale setting. Our work expands and amplifies the range of available emergency sources of high oxygen pressure.

A potential weakness of our study is the analog nature of the oil-filled pressure gauge and the possibility that the needle did not have sufficient time to reach the maximum pressure because of possible damping by the oil. However, during early pilot trials, we held the flush button for prolonged periods and no further increase was noted after the first initial rapid (<1 s) increase to the peak pressure. The oil in the pressure gauge also dampened any oscillations, and a stable reading was readily obtained at all stages. The minimum discrimination of the oil-filled pressure gauge is 3.4 kPa (0.5 psi). However, because of the

§This test was performed on the auxiliary flowmeter of a Draeger Narkomed 6400, which is of the same type and construction as those on the Narkomed 4 machines' auxiliary flowmeters described earlier.

large differences between acceptable and not acceptable working pressures, we do not consider this lack of finer discrimination to be important.

CONCLUSION

We conclude that the working pressures from the common gas outlets of the Narkomed 2B and 4 anesthesia machines, the wall-mounted oxygen flowmeters, as well as the auxiliary oxygen flowmeters of the Datex-Ohmeda Modulus and Excel anesthesia machines are sufficient to use for jet ventilation based on criteria from references mentioned earlier.[3,6]

Wall-mounted oxygen flowmeters do not supply adequate working pressure when the flow is set to the highest scale setting on the flowmeter; jet ventilation requires a greater flow, which is obtained by opening the flowmeters even further (past their "rated" flow). Neither the auxiliary flowmeters of the tested Narkomed anesthesia machines nor the oxygen flush valve of the tested Datex-Ohmeda anesthesia machines will provide sufficient pressures to be used for transtracheal jet ventilation. Because of the variability of a given type of oxygen supply device (e.g., auxiliary oxygen flowmeter), as well as the variability of devices from the same manufacturer, it is important to test each potential high-pressure oxygen source before use to determine whether it actually provides sufficient working pressures during transtracheal jet ventilation.

APPENDIX

Serial numbers of the tested anesthesia machines:

Draeger Narkomed 2B: B-13293, B-14199, B-11035, B-12220, B-14198, B-12218, B-14200, B-12221, B-13294, B-11032, B-11037, B-13289, B-11054, B-11033, B-12219

Draeger Narkomed 4: 10051, 10056, 11547

Datex-Ohmeda Modulus: AMDZ00232, AMFA00259, AMFZ00366

Datex-Ohmeda Excel: AMFZ00367

Serial numbers, respective type numbers of the tested from the wall-mounted oxygen flowmeters:

Timeter (n = 6): 10407003, 10660739, 10533276, 10445860, 10407135, 10407155

Precision (n = 6): Type numbers IMFA 1001, 5MFA1001, 5MFA1081

Datex-Ohmeda (n = 6): AHET31275, AHET31509, AHEX21012, AHET 31242, AHET 31288, AHEX21011

Puritan (n = 6): Series B, no serial numbers available

Commercial Jet ventilator (AINCA, Anesthesia Associates, San Marcos, CA):

There are no serial numbers on the devices (Cat. #00-325).

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