

The Sensitivities and Response Times of Ventilatory Assistors

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The sensitivities and response times of six ventilators in the assist mode were measured. The withdrawal volumes necessary to cause triggering were: Bennett MA-1, 0.5 ml; Bennett PR-2, 1.5 ml; Bird Mark 8, 1.5 ml; Bourns LS 104-150, 0.1 ml; Dräger Spiromat 661, 1.0 ml; Ohio 560, 0.5 ml. The times necessary for the ventilators to respond to these withdrawals were: Bennett MA-1, 82 msec; Bennett PR-2, 226 msec; Bird Mark 8, 157 msec; Bourns, 36 msec; Dräger, 434 msec; Ohio, 123 msec. The maximal rate at which a ventilator can assist is inversely proportional to the response time. (Key word: Ventilators.)

THE GROWTH of intensive care facilities in the last decade has been accompanied by a proliferation of machines for mechanical ventilation. The physician must choose among several expensive devices, generally without the aid of sufficient objective data to compare their performances. Previous reports have been limited largely to descriptions of ventilators in terms of flows and volumes generated and oxygen concentrations delivered under loads. Despite the fact that most modern ventilators feature their ability to assist as well as to control ventilation, few or no reports describing this function are available. In this study a method of quantifying the ability of a ventilator to assist is presented and six ventilators are evaluated.

Methods

We determined the minimum quantity of air which, when rapidly removed from the patient end of the ventilator circuit, caused triggering. Various volumes of air were withdrawn by first storing a vacuum in a syringe

and then exposing the vacuum to the ventilator circuit by manually opening a plastic three-way stopcock as rapidly as possible. The circuit pressure was transduced by a strain gauge (Statham PM 5 or Statham 131), amplified by a carrier preamplifier, and displayed on a storage oscilloscope (Techtronix 564) and photographed. The rise time of this system to a "square-wave" pressure change was 3 msec or less. From the oscilloscope tracing the "response time" and the maximal negative pressure attained were determined for various quantities of air withdrawn. The amount of air withdrawn was increased in increments until a volume which caused triggering at least 90 per cent of the time was found. Since in some ventilator the pressure returned to atmospheric level long before the ventilator triggered, the time from the initiation of negative pressure to the attainment of 1 cm H₂O positive pressure was recorded and is defined as the "response time." An average response time was calculated when the ventilator triggered nine or ten times in ten trials. After determining the response time to the withdrawal of this minimal volume, a relatively large volume was withdrawn to determine if the quantity of air withdrawn materially affected the response time. Except in the case of the Bourns ventilator, this larger volume was 5 ml. Because of the high sensitivity of the Bourns, 0.5 ml was used.

The following ventilators were tested.

PNEUMATICALLY POWERED VENTILATORS

- 1) Bennett PR-2 Special with cascade humidifier (type 1750) and tracheostomy circle (type 1970) (Puritan-Bennett Corp., Kansas City, Mo.). The Bennett PR-2 Special is a commercially available, modified Bennett PR-2 especially designed to cycle at high rates.
- 2) Bird Mark 8 with infant J circuit assembly (type 999 1235) (Bird Corp., Richmond, Calif.).

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ELECTRICALLY POWERED VENTILATORS

1) Bennett MA-1 with pediatric circle tubes (type 5248) but without expiratory spirometer (Puritan-Bennett Corp., Kansas City, Mo.) †

2) Bourns model 104-150 with its standard accessories (16 feet of $\frac{3}{8}$ " i.d. "Tygon" tubing and ultrasonic humidifier filled with 100 ml of water) (Bourns, Inc., Life Systems Div., Riverside, Calif.).

3) Dräger Spiromat 661 with its pediatric bellows and breathing head (K) (North American Dräger, Telford, Pa.).

4) Ohio 560 ventilator with its standard adult circle (Ohio Medical Products, Madison, Wis.).

One of each was tested. All were new or had been reconditioned recently by factory-authorized service facilities. All the ventilators tested except the Ohio 560 are recommended for pediatric use. The Bourns ventilator is suitable only for pediatric use, since the largest tidal volume it can deliver is 150 ml. The remaining ventilators were equipped with their pediatric accessories. In the case of the Bennett respirators these accessories consist mainly of smaller-bore tubing which merely facilitates attachment of the infant to the respirator and decreases the compression volume slightly. In the Bird and Dräger ventilators there are also changes in the valves. The Ohio ventilator was tested in its standard adult version, since no pediatric accessories are available.

With the exception of the Bourns model, the ventilators were set up in a pressure-limited mode (40 cm H₂O). (For adult use the Bennett MA-1, Ohio 560 and Dräger 661 generally are used in a volume-limited mode.) The Bourns ventilator was adjusted to a volume limit of 20 ml and the pressure-relief valve closed so that a peak pressure of 40 cm H₂O developed. (The internal compliance of the Bourns ventilator due to compression of gas is 0.5 cm H₂O/ml.) In those ventilators with flow controls, these controls were set to their

† The expiratory spirometer of the Bennett MA-1 was not used because preliminary studies had shown that this device produces a residual positive pressure during expiration. This positive pressure starts at approximately 1 cm H₂O and decays towards zero. The varying expiratory positive pressure limits the sensitivity of the ventilator. Also, the spirometer is incapable of measuring the very small tidal volumes of infants and thus has no use.

mid-positions. Air entrainment valves, where present, were open.

The sensitivity controls of the Ohio, Dräger, and Bourns respirators were set to their most sensitive positions. ‡ At this setting none of these ventilators exhibited any tendency to trigger automatically. The Bird Mark 8 and the Bennett PR-2 and MA-1 were set at the highest sensitivities possible without causing more than one automatic triggering per minute. The Bennett MA-1 was moderately easy to set, and the setting was stable. The Bennett PR-2 was more difficult to set and required occasional readjustment. The Bird Mark 8, despite its vernier control, was difficult to set, and the setting was not stable. In order to avoid inadvertent automatic triggering, the Bird Mark 8 in clinical practice would be set at a position less sensitive than that used in this study.

Ten trials were made at each volume level with each ventilator. When the ventilator triggered in fewer than nine of the ten trials, it was considered to have failed to trigger. In every such case it actually triggered in fewer than four of the trials. When it triggered in nine to ten of the trials, the means, standard deviations, and standard errors of the negative pressure and the response time were calculated. The single failed trial was disregarded. Where indicated, the coefficient of variation was calculated from the standard deviation to judge the consistency of responses, and the significance of the differences between means was evaluated using Student's *t* test ($P < 0.01$). The significances of such differences were analyzed statistically only when it was judged that the differences were sufficiently large to have clinical significance in terms of coordination of patient and ventilator.

‡ The Ohio ventilator has on its front panel a sensitivity control designed to be adjusted by the physician. There are also internal sensitivity controls. On both of two new Ohio ventilators we have inspected, the internal controls were improperly adjusted, causing the ventilator to be extremely insensitive. The internal controls were properly adjusted for this study, and the data obtained apply only to ventilators so adjusted. The sensitivity of the Ohio also requires that a one-way, preloaded, silicone rubber "flapper valve" in the "patient manifold assembly" remain closed during triggering. That is, it must perform as a "normally closed" one-way valve. On occasion we have had to replace the valve when it ceased to be "normally closed." We do not judge this component to be sufficiently reliable.

TABLE 1. Sensitivities and Response Times of Ventilators

Ventilator	Volume Withdrawn (ml)	Mean Maximum Negative Pressure	(SD, SE)	Mean Response Time	(SD, SE)
		(cm H ₂ O)		(msec)	
Bennett MA-1	0.25	0.21	(0.6, 0.2)	*	
	0.50	0.42	(0.10, 0.03)	82	(3.8, 1.2)
Bennett PR-2	5.0	2.62	(0.18, 0.06)	93	(4.0, 1.3)
	1.0	0.78	(0.18, 0.05)	*	
Bouras LS 104-150	1.5	0.75	(0.10, 0.03)	226	(106, 35)
	5.0	1.31	(0.12, 0.04)	106	(5.2, 1.6)
Bird Mark 8	0.05	0.29	(0.06, 0.02)	*	
	0.10	0.44	(0.09, 0.03)	36	(1.0, 0.3)
Dräger Spiromat 661	0.50	1.50	(0.15, 0.05)	38	(0 , 0)
	1.0	1.55	(0.32, 0.10)	*	
Ohio 560	1.5	1.66	(0.35, 0.11)	157	(45.7, 14.5)
	5.0	1.66	(0.33, 0.10)	87	(10.9, 3.4)
Ohio 560	0.50	1.01	(0.17, 0.05)	*	
	1.0	1.56	(0.21, 0.07)	434	(40 , 13)
Ohio 560	5.0	5.26	(0.28, 0.07)	348	(4 , 1)
	.25	.92	(0.14, 0.04)	*	
Ohio 560	.50	1.94	(0.15, 0.04)	123	(7 , 2)
	5.0	4.61	(0.36, 0.11)	145	(13.5, 4.3)

* Ventilator did not trigger.

Results

The response times of the ventilators at the minimal withdrawal volumes necessary for consistent triggering and at larger withdrawal volumes were determined (table 1). Typical responses at the minimal volumes causing reliable triggering are shown in figure 1. The Bouras ventilator could be triggered upon withdrawal of 0.1 ml and responded in 36 msec. With withdrawal of 0.5 ml the response time was substantially unchanged (38 msec). The Bennett MA-1 triggered with withdrawal of 0.5 ml in 82 msec. Withdrawal of a larger volume prolonged the response time slightly, to 93 msec. The Bennett PR-2 triggered upon withdrawal of 1.5 ml and responded in 226 msec. The response time decreased to 106 msec upon withdrawal of the larger volume. The Bird Mark 8 triggered on withdrawal of 1.5 ml in 157 msec. Withdrawal of the larger volume decreased the response time to 87 msec. The Dräger required 434 msec to respond to withdrawal of 1.0 ml. The response time decreased when a larger volume was withdrawn, but it still was 348 msec. The Ohio ventilator triggered on withdrawal of 0.5 ml in 123 msec. The response time increased slightly, to 145 msec, when the larger volume was withdrawn.

Discussion

Little information concerning the assist function of ventilators has been available, aside from occasional scanty sales notes concerning "sensitivity." In these notes "sensitivity" has generally been taken to mean the static negative pressure at which the ventilator is triggered. Thus, Bouras advertizes that its sensitivity is 0.1 mm H₂O negative pressure. Although we have confirmed this particular specification (unpublished data), it has little meaning. The patient does not apply static negative pressure in order to trigger ventilation. Rather, he withdraws a small volume, which produces an increasing negative pressure. The volume which the patient must withdraw from a system to achieve a given negative pressure is proportional to the volume of the ventilator circuit as well as to tubing compliance. Moreover, in ventilators which have intentional leaks into the circuit (Bird Mark 8, Ohio 560, Bennett PR-2), the rate of withdrawal of gas is a critical determination of the negative pressure attained. In the PR-2, the trigger mechanism is actually sensitive to the flow rather than to the pressure produced by a ventilatory effort.

With our method the peak negative pressures attained were reasonably constant at

each level of withdrawal volume, indicating that our withdrawal technique was consistent. The coefficients of variation of the peak negative pressures were never more than 30 per cent, and, especially at the higher volumes, they generally were less. With every electrically powered ventilator there was an increase in negative pressure with an increase in volume withdrawn. In the two pneumatically powered ventilators, increasing the volumes withdrawn produced little or no significant increases in negative pressure, presumably due to inherent leaks into the systems. However, despite the failure of the peak negative pressures to increase, increases in the volumes withdrawn decreased response times. Apparently the triggering mechanisms are sensitive either to the duration of the negative pressure or to the flow itself.

We have chosen to compare the sensitivities of ventilators in terms of the quantity of gas which must be rapidly withdrawn in order to trigger the ventilator, rather than in terms of static pressure conditions, as the former more closely resembles the clinical situation. It is true, of course, that if the patient withdraws gas slowly, a quantity greater than that indicated by our method may be required.

The Bourns ventilator was exceptionally sensitive, triggering reliably on withdrawal of 0.1 ml. The Bennett MA-1 and Ohio 560 ventilators were a fifth, the Dräger ventilator a tenth, and the two pneumatic ventilators, the Bennett PR-2 and Bird Mark 8, a fifteenth as sensitive. Except for the Bourns, Dräger and Ohio ventilators, periodic readjustment of the sensitivity controls were necessary to achieve this sensitivity. This was considered a serious problem with the Bird Mark 8.

Sensitivity, as we have defined it, is related to the tidal volume, since the volume a patient must withdraw should be small compared with the tidal volume. Thus, we have observed cases of weak, small, or premature infants with tidal volumes of 5 to 15 ml where only the Bourns ventilator had adequate sensitivity. For larger children and adults the sensitivities of all ventilators are adequate. In our practice, for example, we assist respiration in most children more than 18 months of age with the Bennett MA-1.

Sensitivity alone, however, is insufficient to characterize an assistor. It is also essential

that an assistor respond as quickly as possible. The response time of the Bourns ventilator was significantly shorter than those of the other ventilators, and less than half as long as that of the Bennett MA-1, which was next best. The response time of the Dräger ventilator was more than ten times that of the Bourns and was significantly longer than those of the other ventilators. Withdrawal of the larger volumes significantly decreased the response times of the two pneumatic ventilators (Bennett PR-2 and Bird Mark 8) to approximately that of the Bennett MA-1, but affected the other ventilators only marginally.

The response times we have determined are composed of the response times of ventilators themselves plus the propagation times of the pressure waves between patient and ventilator. Assuming the pressure waves travel at the speed of sound, the total propagation time (in msec) is generally twice the distance from the patient to the ventilator (in feet). For the Bourns this is 16 msec, or 44 per cent of the total response time. The propagation time was of little importance in the other ventilators because of their longer response times and their shorter tubing.

Reproducibility of the response times varied. At the lowest volumes causing triggering, the coefficient of variation of the response times of the electrically powered ventilators was less than 10 per cent, while that of the pneumatically powered ventilators was between 30 and 50 per cent. This may be an indication of reliability when high sensitivity is required. With withdrawal of the larger volumes the coefficients of variation were less than 10 per cent for all ventilators.

Until a ventilator actually responds to a patient's inspiratory efforts it acts not as a ventilator, but as a respiratory obstruction. This is especially important in assisted ventilation at high rates with the correspondingly limited inspiratory times. If the response time comprises a large part of the inspiratory time the patient will be observed to retract during the first part of the inspiration. This problem is compounded in ventilators such as the Dräger, which have low initial flows during inspiration. This effect may be less if by his own inspiratory effort the patient can directly draw in gas through a relatively low-resistance valve, as in the Ohio 560. However, to the extent that

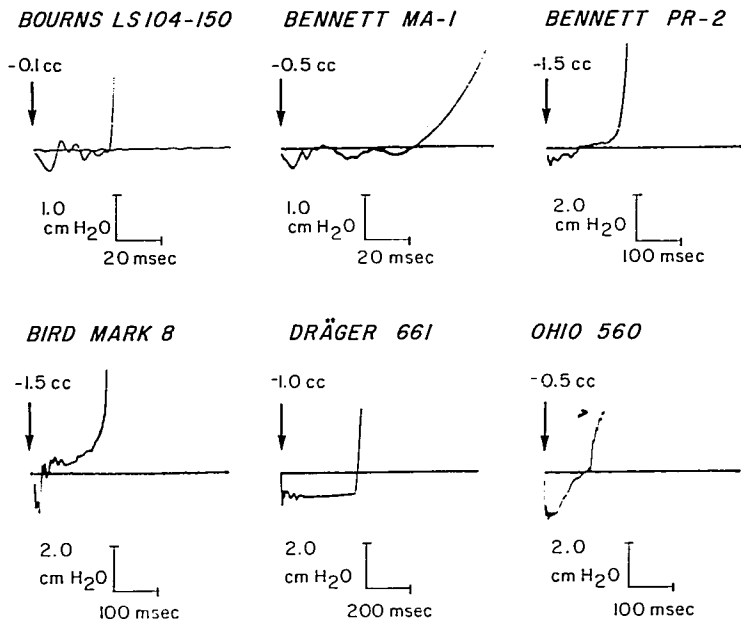


FIG. 1. Response times of ventilators to withdrawal of minimal volumes which cause reliable triggering. Withdrawal is indicated by arrow. Horizontal line is atmospheric pressure. Note that volumes withdrawn, and time and pressure scales, vary.

this occurs the patient is not in fact being "assisted." Such useless work by a patient in respiratory failure must be assumed to be detrimental. It is certainly reasonable to insist that the response time of a ventilator be no more than 10 per cent of the total time of inspiration. This would set the minimum inspiratory time at ten times the response time. For the ventilators studied, the minimal inspiratory times under conditions of maximum sensitivity would then be: Bourns 0.36 sec; Bennett MA-1, 0.82 sec; Ohio 560, 1.23 sec; Bird Mark 8, 1.57 sec; Bennett PR-2, 2.26 sec; Dräger, 4.34 sec. If we were to allow inspiration to be as high as 50 per cent of the total respiratory cycle, then the maximal permissible rates would be: Dräger, 7; Bennett PR-2, 13; Bird Mark 8, 19; Ohio 560, 24; Bennett MA-1, 37; Bourns, 83. In the larger child or adult

who may be permitted to withdraw a larger volume before the ventilator triggers, the response time may be altered. Using the response times calculated from our withdrawal of larger volumes the maximal permissible rates would be: Dräger, 9; Ohio 560, 21; Bennett PR-2, 28; Bird Mark 8, 34; Bennett MA-1, 32; Bourns, 79. It has been our clinical experience that when assistance at an appreciably higher rate is attempted noncoordination with the machine results.

The maximal assist rates that we have calculated assume that the only significant time lag is within the ventilator itself. We have observed patients with very high airway resistances in whom there was an additional lag between the inspiratory effort, as judged by muscle activity or changes in intrapleural pressure, and the development of negative airway pres-

sure (unpublished observations). In such cases the total "response time" from initiation of inspiration to machine response is much longer, further limiting the maximal assist rate or even making assistance impossible in the presence of an extreme phase difference.

With its extreme sensitivity and rapid response time, the Bourns ventilator is uniquely useful in assisting respiration in small infants at high rates. For the small child who can easily withdraw a few milliliters of air, the MA-1 is suitable if the tidal volume chosen is large enough to avoid the necessity for assistance at very high rates. The MA-1 is capable of delivering much higher flows and volumes than the Bourns, as is required in the larger child.

We have had no clinical experience using the Ohio 560 in a pressure-limited mode for the small child, but its performance suggests that it might have application at moderate rates. Although the Bennett PR-2 and the Bird Mark 8 have fairly good triggering characteristics for use in the small child, their poorer stability and their difficulties in deliver-

ing predictable, safe oxygen concentrations without additional accessories make them second choices. The Dräger Spiromat 661 is useless as a pediatric assistant because of its excessively long response time.

All of the ventilators except the Bourns model are available with accessories which make them suitable for ventilation of adults. Sensitivities and response times are not significantly different when these ventilators are equipped for adults (unpublished observation). Although in ventilation of adults sensitivity as defined in terms of volume withdrawn is of minor importance, response time still limits the maximum permissible rates of assistance. This limitation is not so serious when ventilating adults since low rates with concomitantly long inspiratory times generally are desired. Although the Bennett MA-1 is capable of the highest rates, all of the ventilators tested except the Dräger Spiromat 661 have response time adequate for moderate rates of assistance. The Dräger Spiromat must be considered primarily a controller, although occasional patient triggering may be allowed.

Drugs

ISOPROTERENOL TOXICITY Isoproterenol injected twice in 48 hours caused large intramural hematomas in the cardiac wall at the site of aneurysm formations in frogs kept at 25 to 29 C. (Poupa, O., and Carlsten, A.: *Isoproterenol-induced Cardiac Lesions in Frog Observed In Vivo*, *Canad. J. Physiol.* 48: 306 (May) 1970.)

DOPAMINE IN BURNS Three severely burned patients were infused with dopamine-2-¹⁴C, the immediate precursor in the biosynthesis of norepinephrine. Infusion was purposely delayed until three weeks after the burn, since depletion of catecholamines most commonly manifests itself at this time. There were marked decreases in the percentages of radioactivity recovered in the urine as norepinephrine in all collection periods, in contrast to results in normal subjects, from whom radioactive norepinephrine was recovered after 24 hours. Concomitantly, there was an increase in radioactivity recovered as metabolic products of norepinephrine, reflecting a compensatory shift toward norepinephrine synthesis and utilization at the expense of the dopamine metabolic products. In the burned patients, dopamine-2-¹⁴C was rapidly synthesized into epinephrine and then rapidly released and metabolized. These results suggest that dopamine might be a useful adjunct in the treatment of sympathico-adrenal medullary depletion following burns. (Goodall, McC., and Alton, H.: *Dopamine (3-Hydroxytyramine) Replacement and Metabolism in Sympathetic Nerve and Adrenal Medullary Depletions after Prolonged Thermal Injury*, *J. Clin. Invest.* 48: 1761 (Sept.) 1969.)