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A Bench Study of New-Generation Anesthesia Ventilators: Inspiratory Trigger Sensitivity in Pressure-Support Mode

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ABSTRACT

Purpose: The new-generation anesthesia ventilators are better at synchronizing with a patient's spontaneous respirations, which is important for intensive care. The aim of our study was to evaluate different anesthesia ventilators in pressure-support ventilation mode with regard to aspects of their trigger sensitivity to spontaneous inspiratory breathing.

Methods: Four anesthesia machines and one intensive-care ventilator were evaluated. The ventilators were connected to a spontaneously breathing test lung. Each anesthesia machine used a different technology for recognizing the change in gas flow, and different flow generators. The trigger sensitivity, the percentage of triggering failures, and the lag time occurring at the time of an intake of air intake were investigated.

Results: The intensive-care ventilator had the highest trigger sensitivity. The trigger sensitivity of the 4 anesthesia machines was also high. The anesthesia machines from most to least sensitive were as follows: machines equipped with a hot-wire flow meter, an ultrasonic flow meter, or a differential pressure-flow meter. In addition, other structural differences between the machines affected the differences in sensitivity.

Conclusion: The differences between the trigger sensitivity of the tested anesthesia ventilators were a result of differences in the flow-triggering mechanisms and other structures. Although no anesthesia machines had higher trigger sensitivity than the intensive-care ventilator, the anesthesia machine most recently on the market had very similar trigger sensitivity.

Key words: Anesthesia ventilator・Trigger sensitivity・Pressure support ventilation

Introduction

Possessing an "educated hand" that can control ventilation during anesthesia is thought to be essential for an anesthesiologist. Performing manual ventilation is not difficult for patients without spontaneous breathing, because the patient's respirations depend solely on mechanical ventilation. However, for patients with spontaneous breathing, performing manual ventilation is difficult.

The new-generation anesthesia ventilators can now be used in pressure-support mode, which had already been a feature of ventilators used in intensive care units. Synchronization with the patient's spontaneous breathing is an important function of anesthesia ventilators, and the most recent anesthesia machines have been developed to provide synchronicity[1), 2)]. Pressure support ventilation (PSV) is a ventilator mode that assists the patient's breathing with a preset pressure control when the machine detects an inspiratory effort. PSV is widely used in intensive

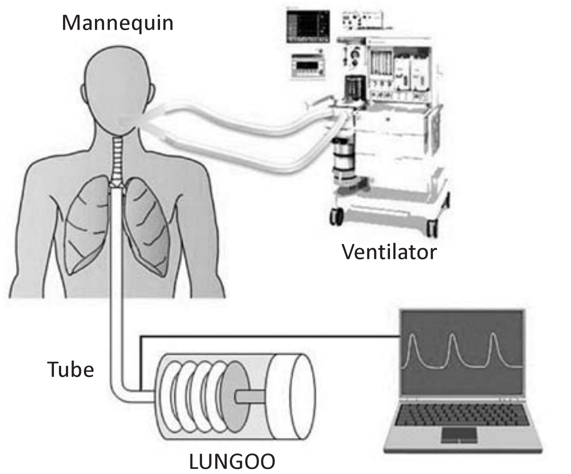

Fig. 1. Simulation system
Connected each ventilator to the LUNGOO through Mannequin, we made a simulation system like this. The computer observed some factors in real time at connected tube.

care units. It can shorten the time lag between a spontaneous breath and ventilator support, thereby decreasing the patient's respiratory effort and time to weaning from the ventilator[1), 3)−9)]. Although the pressure changes in the ventilatory circuit had been used for triggering, flow-trigger pressure-support ventilation is now used by many anesthesia ventilators because of the short duration of negative pressure[2), 9)].

Patient-ventilator synchronization provided by the new-generation anesthesia ventilators in PSV mode has not been studied. We evaluated the following 4 anesthesia machines, each of which used a different method for detecting changes in flow: the Flow-i (Maquet, Sweden), Perseus A500 (Dräger, Germany), Primus IE (Dräger), and Aisys™ (GE Healthcare, USA). An intensive-care-unit (ICU) machine, the Puritan Bennet (PB) 840 ventilator (Covidien, USA), was used as the control.

Methods

The 4 test anesthesia ventilators (Perseus A500, Primus IE, Flow-i, Aisys) and PB840 ICU control ventilator were evaluated in 3 different experiments. These machines were the newest ventilators introduced for use at Yamagata University Hospital, and were chosen for investigation to validate their clinical utility. A mannequin with a spontaneously breathing test lung (Lungoo, Air Water Safety Service INC, Kobe, Japan) was connected to the ventilator (Fig. 1). The respiratory rate (RR) and simulated respiratory muscle pressure (Pmus) provided by the Lungoo were changed based on the experiment. Each ventilator generated positive end-expiratory pressure (PEEP) and pressure support (PS).

The Lungoo uses a piston that automatically moves to simulate spontaneous inspiration and expiration[10)]. The Lungoo settings for simulating the respiration of a healthy adult of normal size were as follows: inspiration time 1.0 s, standup coefficient 0.2 s, falling coefficient 0.05 s, functional residual capacity (FRC) 400 mL, inspiratory/expiratory (IE) ratio 1:2, compliance 70 mL/cmH_2O and airway resistance 5.0 cmH_2O/L/s.

The settings of the anesthesia ventilators were as follows: inspiration time 1.0 s, flow trigger 1.0 L/min, and 25 % of expiration sensitivity. The display style for the flow trigger of the Flow-i ventilator was different from the other anesthesia ventilators and was adjusted. A flow trigger level of 6 on the Flow-i machine was equivalent to the flow trigger of 1.0 L/min on the 3 other types of anesthesia ventilators. The tube that connected each anesthesia ventilator with the Lungoo used the same thing and the PB840 used the attached one.

The synchronization of each test anesthesia ventilator was compared to the PB840 ventilator. How is the influence to the respiratory pattern of synchronizing about the PEEP, RR, PS and Pmus that is inspiratory effect by the test lung, Lungoo?

The following 3 experiments were performed:

Experiment 1

Observing a waveform in real time, we increased the Pmus for every 1.0 cmH_2O from 1.0 cmH_2O, and recorded the minimum Pmus that carried out the trigger of spontaneous breathing. If the trigger was carried out, it was considered successful. If the trigger was not carried out and the ventilator shifted to enforced ventilation, the ventilator was determined to have no perception. The minimum Pmus value was determined for the following settings as follows:

PEEP (0, 10 cmH_2O), RR (5, 10, 15, 30 breaths /min), and PS (0, 5, 10 cmH_2O).

Experiment 2

The rate of ineffective effort provided by the ventilators was determined from the differences in RR between the Lungoo and each ventilator. Ineffective effort is the failure of triggering an inspiration[11]. The PS was set at 10 cmH_2O, and the following setting were used: PEEP was changed from 0 to 10 (0, 5, 10 cmH_2O), and RR 5 to 30 (5, 10, 15, 30 breaths/min). The following is an example that shows the method used for determining the rate of ineffective effort: if the RR of the Lungoo was 30 breaths/min and the tested respirator produced a RR of 10 breaths/min, the rate of ineffective effort was calculated as ([30-10 breaths] divided by 30) x 100 = 66 %. The result indicates 66 % of respiration failed to trigger inspiration.

Experiment 3

The time from the initiation of air intake by the Lungoo to the trigger of inspiration by each ventilator was measured. The time was measured from the flow waveform at the inlet of the Lungoo tube. The RR was set at 15 breaths/min, and the following settings were used: PEEP (0, 10 cmH_2O), PS (5, 10 cmH_2O), and Pmus (1, 3, 5, 7, 9 cmH_2O).

These experiments evaluated synchronization of the ventilator with triggering and voluntary respirations by investigating the degree of successful triggering, rate of unsuccessful triggering, and the degree of delay by the minute environment.

Results

Experiment 1

For a PEEP set up 0 (Fig. 2A), the PB840 and the Perseus A500 was triggered at minimum Pmus of 1 cmH_2O under all conditions. The Aisys was triggered at a Pmus of 2 cmH_2O under all conditions. The Primus IE and the Flow-i were triggered at a Pmus of 2 cmH_2O at high RR values and low PS values, and the Primus IE showed better sensitivity than the Flow-i at 5 points.

For a PEEP set up at 10 cmH_2O (Fig. 2B), the PB840 was triggered at minimum Pmus of 1 cmH_2O under all conditions. The Flow-i was triggered at a Pmus of 2 cmH_2O under all conditions. At high RR values and low PS values, the Perseus A500 triggered at Pmus of 2 cmH_2O at one point, the Primus IE was triggered at Pmus of 2 cmH_2O under 3 condisions, and the Aisys was triggered at a Pmus of 3 cmH_2O at one point.

For the 4 anesthesia machines, low RR values and high PS values resulted in low minimum Pmus values that led to triggering. When PEEP was changed, the trigger sensitivity of the Flow-i and Aisys machines decreased. The Flow-i changed from 1 cmH_2O to 2 cmH_2O at low RR and high PS values, and the Aisys was triggered at 3 cmH_2O, 30 RR, 0 PS. There was no change in sensitivity for the Perseus A500, Primus IE and PB840 ventilators. The PB840 always demonstrated higher flow trigger sensitivity than the test anesthesia machines. However, the trigger sensitivity of the 4 anesthesia machines was excellent; and highest for the Perseus A500, followed in order of decreasing sensitivity by the Primus IE, Flow-i, and Aisys (Fig. 2A, B).

Experiment 2

With PEEP set at 0, the Aisys and the Flow-i showed a 100% triggering failure rate at a Pmus of 1 cmH_2O. The Primus IE also showed 100% triggering failures at Pmus values of 1 and 2 cmH_2O and RR at 30/min. With PEEP increased to 10, the Aisys showed a 100% triggering failure rate at a Pmus of 1 cmH_2O and the Flow-i was at Pmus 1 cmH_2O and RR 15, 30/min (Fig. 3A).

With PEEP set at 10, the Aisys and the Flow-i showed a 100% triggering failure rate at a Pmus of 1 cmH_2O (Fig. 3B).

With low Pmus values and high RR values, all of the test machines showed a 100% triggering failure rate for spontaneous respirations. Differences in the rates of ineffective effort were observed. The rates of ineffective effort increased with increasing PEEP. Although the PB840 and Perseus A500 carried out the trigger under all experimental conditions, the 3 anesthesia machines did not carry out the trigger under some conditions. The highest rate of the

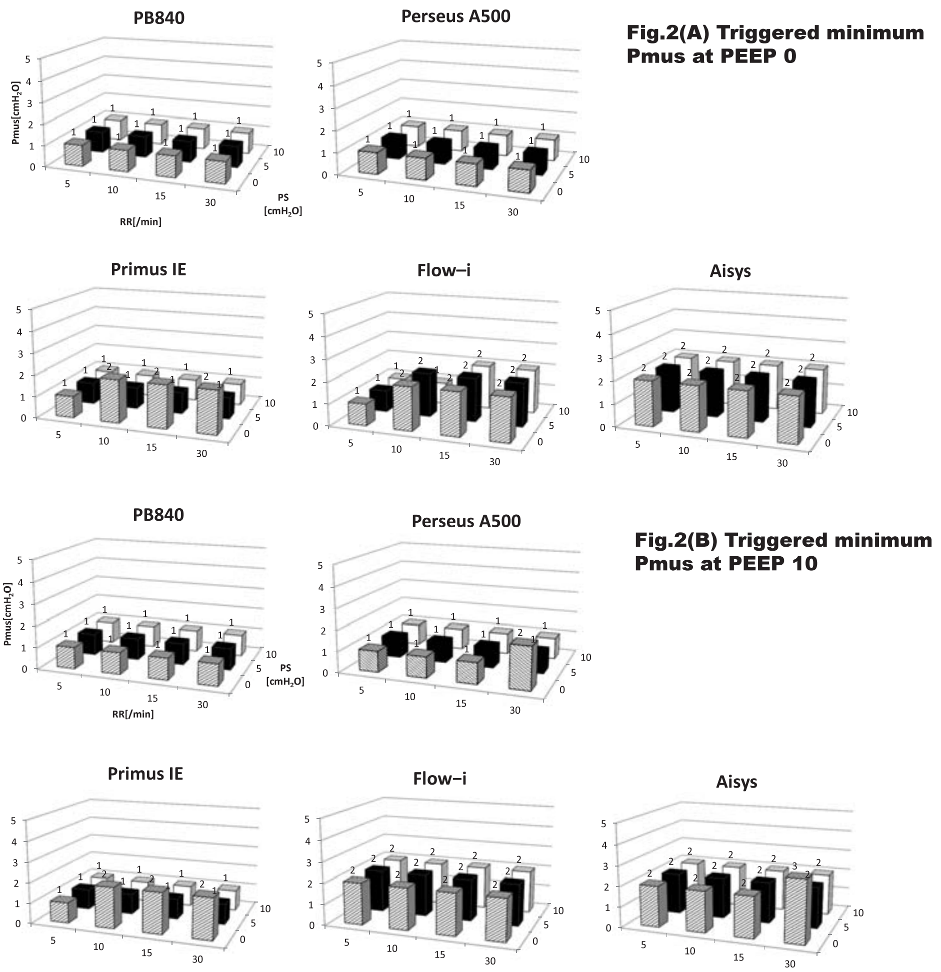

Fig. 2.

(A) Minimum Pmus necessary to trigger spontaneous breath at PEEP 0 cmH_2O and different levels PS and RR. Primus IE and Flow-i tended to be unable to trigger at higher RR and lower PS.

(B) Minimum Pmus necessary to trigger a spontaneous breath at PEEP 10 cmH_2O and different levels PS and RR. Primus IE and Aisys tended to be unable to trigger at higher RR and lower PS. Comparison with PEEP 0, PB840, Perseus A500 and Primus IE showed same performance. On the other hands, Flow-i and Aisys had lower sensibility at higher PEEP.

successful triggering for the Perseus A500 was at a PEEP of 0, and the rates of the successful triggering decreased in order of the PB840, Primus IE, Flow-i, and Aisys (Fig. 3A). However, at a PEEP of 10, the rate of the successful triggering in the PB840 was higher than that for the Perseus A500 (Fig. 3B).

Experiment 3

The Perseus A500 showed less than a 0.1s delay under all conditions. Other 4 machines happened trigger delay or not triggered at Pmus 1 cmH_2O. The PB840 showed more than a 0.1s delay except for PEEP set at 0 and PS at 5. The Primus IE showed less than a 0.1s delay at PEEP set at 0 and PS 5 but more than a 0.1s delay at high PEEP and high PS. The Aisys and the Flow-i did not trigger at a Pmus of 1 cmH_2O. All machines showed the same results at Pmus values of 3, 5, 7 and 9 cmH_2O (Fig. 4).

With high Pmus values, the time from the initiation of air intake by the Lungoo to the trigger of inspiration by each ventilator was decreased, and the effects of PEEP and PS were diminished. The time from the initiation of air intake by the Lungoo to the trigger of inspiration by the Perseus A500 was the

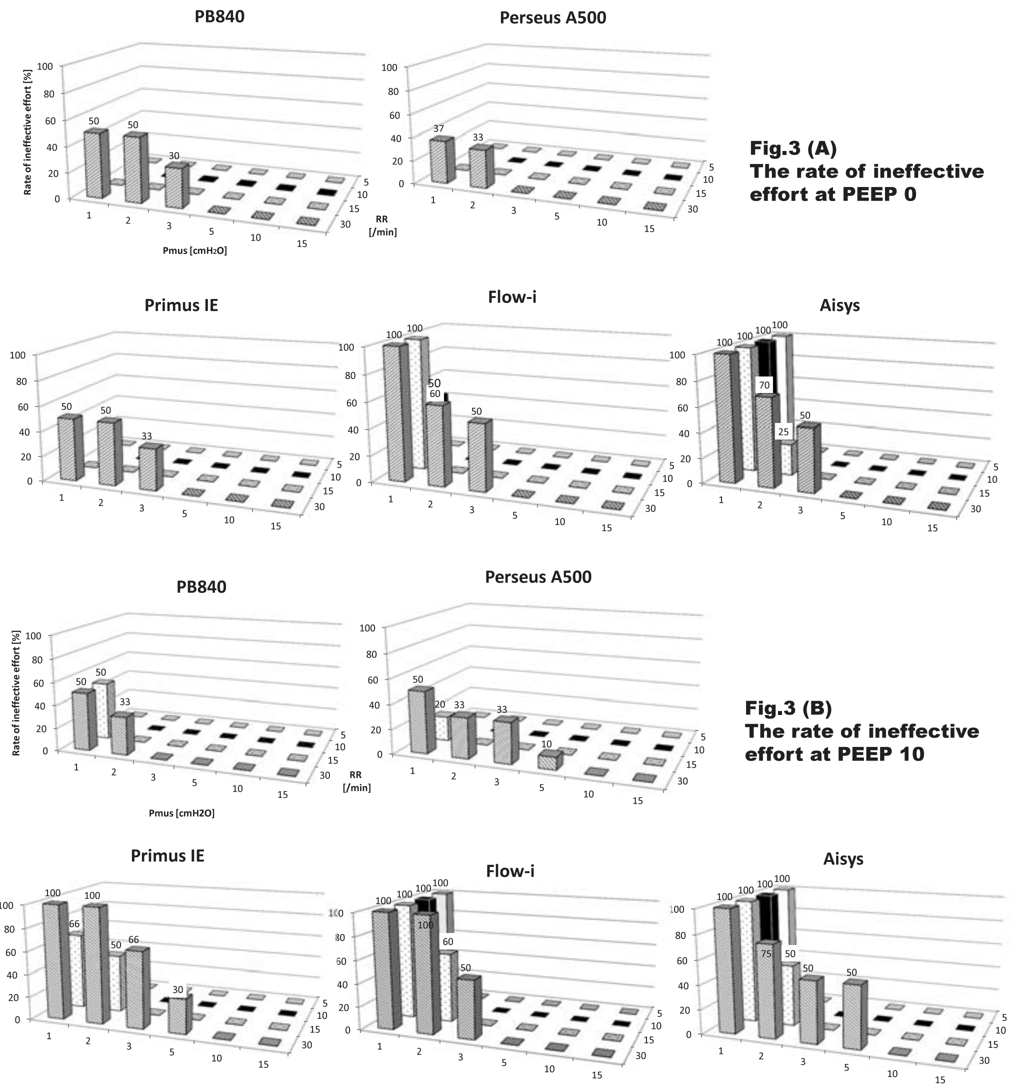

Fig. 3.
(A)(B) Rate of ineffective effort (0-100%) with constant PS (10 cmH_2O) at different levels of PEEP, Pmus and RR. All ventilators become less sensitive at higher PEEP, lower Pmus and higher RR. The ineffective effort is failure of triggering. Even if the inspiration is beginning, the triggering is not occurred. We calculated this rate at PEEP 0 cmH_2O and 10 cmH_2O.

shortest compared to the other machines.

Discussion

When Ventilator is used for a patient with voluntary respiration, deterioration in the synchronization between the ventilator and the patient's respirations is said to leads to a pulmonary obstacle. Anesthesia ventilators providing excellent synchronization are greatly needed. This research estimated the difference in triggering, and it was considered from what its difference occurred.

The PB840, which was the ICU ventilator that we used in this study, has a hot wire flow meter. Since it has the best design features and is equipped with the best devices for trigger sensitivity, our finding that the PB840 had the highest sensitivity under almost all experimental conditions is not surprising (Fig. 5). A minimum Pmus of less than 2 cmH_2O for triggering may not be clinically important for patients with normal lungs; however, patients with conditions such as chronic obstructive pulmonary disease require a

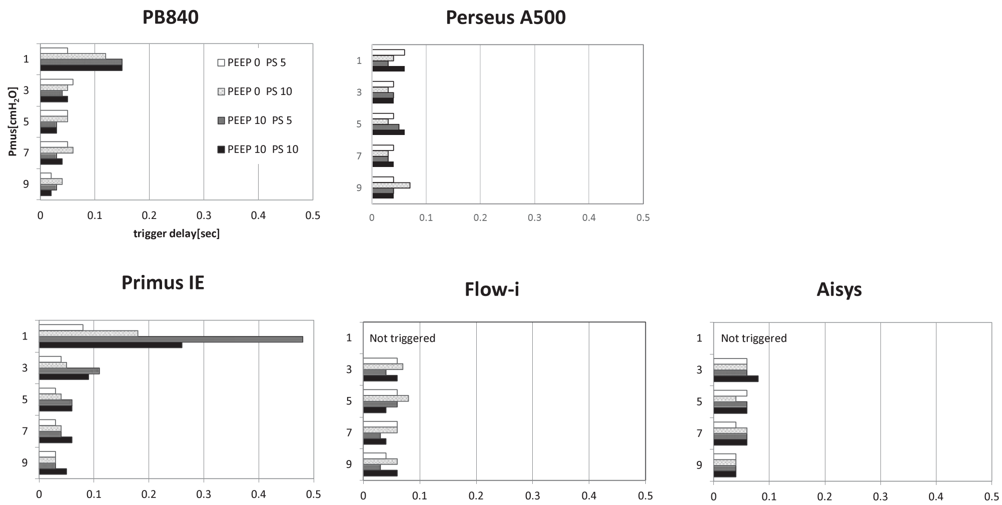

Fig. 4. The trigger delay

Time to inspiratory trigger at different levels of PEEP, PS and Pmus (RR = 15/min). The time tended to be shorter at higher Pmus.

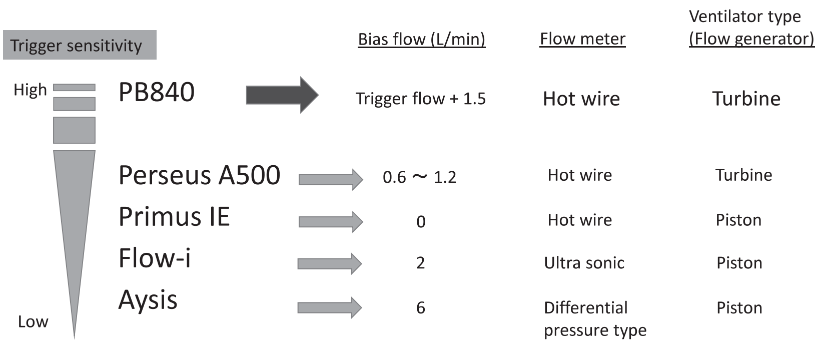

Fig. 5. Some factors to determine trigger sensitivity

We investigated about the bias flow rate, the flow meter, and the ventilator type of each anesthesia machines. PB840 and Perseus A500, performed good sensitivity, have same structure. On the other hand, the effect of bias flow was not clear in this study.

trigger sensitivity that accommodates a Pmus of less than 2 cmH_2O.

From the results of experiments 1 and 2, lower PEEP, fewer RR, higher Pmus, and higher PS, increased the trigger sensitivity, and the contrary condition became bad. These 4 parameters affect the ease of breathing and size of tidal volume. That is, a lower PEEP is good for deep breathing, a low RR leads to large tidal volume, and the high Pmus and PS values lead to increased vigor of breathing. For that reason, it was observed that the rate of flow change through the inside of circuit becomes large, and is easy to be triggered[9]. Moreover, in experiment 3, although the Pmus was seen to affect the time to air intake, variation in PEEP and PS values led to varied results. A previous study evaluating new-generation anesthesia ventilators also found that the effect of PEEP and PS on time to air intake differed between different types of anesthesia machines[1].

From these results, the intensive-care ventilator had the highest trigger sensitivity. The anesthesia machines from most to least sensitive were as follows: Perseus A500, Primus IE, Flow-I and Aisys. Although we investigated these ventilators under conditions that were as similar as possible, they had different trigger sensitivities. Some structural features were involved, as we describe in the following paragraphs.

Effect of bias flow

Differences in the trigger sensitivity of different types of ventilators are generally considered to be a result of a bias flow through the ventilation circuit that inhibits the ability of the ventilator to detect the initiation of spontaneous inspiration. Then, we investigated the bias flow rate of each anesthesia machine. The following bias flows were found: Perseus A500 was 0.6 to 1.2 L/min, Primus IE 0 L/min, Flow-i 2 L/min and Aisys 6 L/min. Generally, with fresh gas providing bias flow, the trigger sensitivity of a machine is high, because the flow through the circuit is stabilized. However, there have been some studies showing that high bias flow increases the work of breathing or results in longer breathing time during PSV[12)−14)]. In our study, bias flow might have affected trigger sensitivity, but the incidence was not clear.

Effect of flow meter

The Aisys used a differential pressure flow meter, the Flow-i used an ultrasonic flow meter, and the Perseus A500 and the Primus IE used a hot wire flow meter. The differential pressure flow meter determines the gas flow rate from the difference in pressure before and after squeeze mechanisms. The differential pressure flow meter has a wide scope, simple design, and is inexpensive. However, the meter has low accuracy, and the connecting pipe is easily blocked. Therefore, it was thought that Aisys is most inferior trigger sensitivity was brought.

The ultrasonic flow meter sends an ultrasonic wave to the fluid in piping, and determines the flow rate in the tubing using the penetration signal and reflected signal[15)]. The ultrasonic flow meter is comparatively accurate. However, it is affected by turbulence and vortices in the gas flow. In addition, it is expensive.

The hot wire flow meter measures flow using a heated wire. An electronically heated wire touches a pipeline, and the meter uses the change in temperature of the wire to calculate the flow rate[16)]. The strengths of the hot wire flow meter are that maintenance is unnecessary and failure is rare. Since there is no flexible region which can measure a mass flow rate directly in this flow instrument, once it operates, the flow meter can measure continually. Moreover, it can measure very low flow rates, such as 3 NmL/min (N means the value in the air at the standard state) for gas flow and 0.7 mL/min for liquid flow, and because the temperature sensor continues taking out an output signal even if the flow velocity approaches zero, the signal does not suddenly disappear. The meter can be used at temperatures ranging from +550 ℃ to -200 ℃. Therefore, the hot wire flow meter has highly accurate trigger sensitivity, as shown by the Primus IE anesthesia machine.

Effect of flow generator

There were 2 types of flow generators in the machines of this study, the piston ventilator and turbine ventilator. The Primus IE, Flow-i and Aisys are equipped with a piston. The PB840 and Perseus A500 are equipped with a turbine. The turbine ventilator is more sensitive than the piston. The turbine produces a more stable flow, so that there is less turbulence in the flow circuit and the flow meter can sensitively detect the change in flow during low-flow states[17)].

Effect of ventilation circuit and other factors

The differences between the anesthesia machines we studied and the intensive care ventilator used as the control include differences in the ventilation circuit and other factors. The anesthesia machines have a larger ventilation circuit capacity (respiratory gas module) than the intensive care ventilator. The position of the trigger sensor of anesthesia machines is far from the patient side. The anesthesia machines have many expiration and inspiration valves, so resistance due to friction is high, and the resistance in a circuit by ancillary equipments is high[7)]. From these points, it is possible that trigger sensitivity of the anesthesia machines is worse than the ICU ventilator.

There are also differences in the design of the circuits. Anesthesia machines have an open circuit, which allows the effective use of anesthetic gases. Therefore, anesthesia machines require 2 circuits, a breathing circuit and a reservoir circuit. By contrast, the ICU ventilator has a completely closed circuit[1), 4), 7), 17)]. Since there is only a breathing circuit, this is a simple system with a small circuit capacity, therefore, its reactivity is good.

Study Limitations

This study has some limitations. We investigated these ventilators using conditions as similar as possible for each ventilator; however, setting up the same flow trigger levels was difficult. There might have been very small differences between levels because of intrinsic features. Moreover, our simulation system did not have a humidifier, and the effect of humid flow is important to ascertain. Finally, only 4 anesthesia ventilators were investigated, and more information is needed on other ventilator models for quantitative evaluation.

Conclusions

There were differences in the trigger sensitivity and triggering systems between the new-generation anesthesia machines and the ICU ventilator. The new-generation anesthesia machines in order of increasing sensitivity were as follows: the Perseus A500, the Primus IE, Flow-i, and Aisys. The differences in trigger sensitivities can generally be attributed to the different mechanisms of flow triggering.

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