Performance of Ventilators Compatible With Magnetic Resonance Imaging: A Bench Study

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BACKGROUND: Magnetic resonance imaging (MRI) is indispensable for diagnosing brain and spinal cord abnormalities. Magnetic components cannot be used during MRI procedures; therefore, patient support equipment must use MRI-compatible materials. However, little is known of the performance of MRI-compatible ventilators. METHODS: At commonly used settings, we tested the delivered tidal volume (V_T), F_{IO_2}, PEEP, and operation of the high-inspiratory-pressure-relief valves of 4 portable MRI-compatible ventilators (Pneupac VR1, ParaPAC 200DMRI, CAREvent MRI, iVent201) and one ICU ventilator (Servo-i). Each ventilator was set in volume control/continuous mandatory ventilation mode. Breathing frequency and V_T were tested at 10 breaths/min and 300, 500, and 700 mL, respectively. The Pneupac VR1 has fixed V_T and frequency combinations, so it was tested at V_T = 300 mL and 20 breaths/min, V_T = 500 mL and 12 breaths/min, and V_T = 800 mL and 10 breaths/min. F_{IO_2} was 0.6 and 1.0. At the air-mix setting, F_{IO_2} was fixed at 0.5 with the Pneupac VR1, 0.45 with the ParaPAC 200DMRI, and 0.6 with the CAREvent MRI. PEEP was set at 5 and 10 cm H_2O, and pressure relief was set at 30 and 40 cm H_2O. RESULTS: V_T error varied widely among ventilators (−28.1 to 25.5%). As V_T increased, error decreased with the Pneupac VR1, ParaPAC 200DMRI, and CAREvent MRI ($P < .05$). F_{IO_2} error ranged from −13.3 to 25.3% at 0.6 (or air mix). PEEP error varied among ventilators (−29.2 to 42.5%). Only the Servo-i maintained V_T, F_{IO_2}, and PEEP at set levels. The pressure-relief valves worked in all ventilators. CONCLUSIONS: None of the MRI-compatible ventilators maintained V_T, F_{IO_2}, and PEEP at set levels. Vital signs of patients with unstable respiratory mechanics should be monitored during transport and MRI. *Key words: magnetic resonance imaging; MRI; MRI-compatible ventilator.* [Respir Care 2015;60(3):341–346. © 2015 Daedalus Enterprises]

Introduction

Magnetic resonance imaging (MRI) has become essential for diagnosing abnormalities in the brain, spinal cord, spine, and major joints that are undetectable using conventional imaging techniques. Many patients require ventilatory support during transport and the MRI procedure. In MRI suites, conventional ventilators with ferromagnetic components have a number of issues, including risk of projectile events, degradation of image quality, and compromised ventilator performance.[1,2] Portable ventilators do not perform as well as ICU ventilators[3]; in addition, MRI-compatible ventilators have their ferromagnetic components replaced with non-ferromagnetic components made of aluminum alloy and other materials. Although regular delivery of accurate tidal volume (V_T), PEEP, and F_{IO_2} is crucial for critically ill patients, we found few studies detailing the performance of MRI-compatible portable ventilators. Consequently, in a non-MRI environment, we carried out this bench study to evaluate the performance of MRI-compatible portable ventilators.

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The authors have disclosed no conflicts of interest.

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Methods

Ventilators Tested

Along with one ICU ventilator (Servo-i, Maquet, Wayne, New Jersey) used as a control, we tested 4 portable MRI-compatible ventilators: Pneupac VR1 (Smiths Medical, Watford, United Kingdom), ParaPAC 200DMRI (Smiths Medical), CAREvent MRI (O-Two Medical Technologies, Mississauga, Ontario, Canada), and iVent201 (GE Healthcare, Madison, Wisconsin) (Table 1). We checked the accuracy of delivered V_T, F_{IO_2}, PEEP, and alarm function of high-airway-pressure relief.

V_T and Breathing Frequency

All ventilators were tested in volume control/continuous mandatory ventilation mode. The Pneupac VR1 offers only fixed combinations of V_T and breathing frequency: it was tested at 300 mL and 20 breaths/min, 500 mL and 12 breaths/min, and 800 mL and 10 breaths/min. With the other ventilators, breathing frequency was set at 10 breaths/min, and V_T was set at 300, 500, and 700 mL.

F_{IO_2}

Two levels of F_{IO_2} (1.0 and air mix) were available with the Pneupac VR1 (air mix, $F_{IO_2} = 0.5$), ParaPAC 200DMRI (air mix, $F_{IO_2} = 0.45$), and CAREvent MRI (air mix, $F_{IO_2} = 0.6$). On the iVent201 and Servo-i, F_{IO_2} was set at 1.0 and 0.6.

PEEP

PEEP on the CAREvent MRI, iVent201, and Servo-i was set at 5 and 10 cm H_2O. To apply PEEP, the Pneupac VR1 and ParaPAC 200DMRI required a PEEP valve with spring, a ferromagnetic component that would be unsuitable for use in an MRI suite.

Alarm Function of High-Pressure-Relief Valves

The alarm function of high-pressure relief was tested at 30 and 40 cm H_2O with V_T set at 1,000 mL and compliance of 0.02 L/cm H_2O (peak inspiratory pressure was $>$ 50 cm H_2O). With the Pneupac VR1, the available fixed value was 40 cm H_2O.

Compliance and Resistance

The compliance of the TTL test lung (model 1601, Michigan Instruments, Grand Rapids, Michigan) was adjusted to 0.05 and 0.02 L/cm H_2O with a resistance of 5 and 20 cm H_2O/L/s, respectively (see Table 1).

QUICK LOOK

Current knowledge

Magnetic resonance imaging (MRI) has become essential for diagnosing abnormalities in the brain, spinal cord, and spine. Many patients require ventilatory support during transport to and during magnetic resonance imaging. In MRI suites, conventional ventilators can contribute to risk of projectile events, degradation of image quality, and compromised ventilator performance.

What this paper contributes to our knowledge

None of the MRI-compatible ventilators maintained V_T, F_{IO_2} and PEEP at set levels. Additional monitoring of vital signs in patients with unstable respiratory mechanics should be performed during transport and MRI.

Experimental Setup

Each ventilator was connected to a TTL test lung via the supplied or standard limb tubing. With the iVent201 and Servo-i, compression volume was corrected with self-test procedures. An oxygen analyzer (S/5 compact monitor, GE Healthcare), pressure transducer (TM6600, San-You Technology, Saitama, Japan), and pneumotachometer (4700 series, 0–160 L/min, Hans Rudolph, Shawnee, Kansas) were placed between the Y-piece of the ventilator limb and the TTL test lung. The pneumotachometer was connected to a differential pressure transducer (TP-602T, $\pm$5 cm H_2O, Nihon Kohden, Tokyo, Japan) to measure flow (Fig. 1). The oxygen analyzer was self-calibrated automatically at an F_{IO_2} of 0.21, and the pneumotachometer was calibrated using a 1.0-L supersyringe. We monitored flow, F_{IO_2}, and airway pressure for 15 min, and after confirming the constancy of the values, we recorded them for 1 min. Each signal was processed through an analog-to-digital converter and saved on a computer at 50 Hz/channel using data acquisition software (WinDaq, DATAQ Instruments, Akron, Ohio). Delivered V_T was calculated later by digital integration of expiratory flow signals.

Analysis and Statistics

Values were shown as percent error:

$$\%\text{error} = 100 \times (\text{measured value} - \text{set value})/\text{set value}.$$

Statistical analysis was performed using repeated-measures analysis of variance. All statistical tests were 2-sided. Statistical analysis was performed using commercial soft-

Table 1. Tested Ventilators and Experimental Settings

Model	Manufacturer	V_T (mL)	F_{IO_2}	Compliance (L/cm H_2O)	Resistance (cm H_2O/L/s)	PEEP (cm H_2O)	Safety Valve of PIP (cm H_2O)
Pneupac VR1	Smiths Medical	300 (20), 500 (12), 800 (10)*	1.0, 0.5	0.05, 0.02	5, 20	Non	40
ParaPAC 200DMRI	Smiths Medical	300, 500, 700	1.0, 0.45	0.05, 0.02	5, 20	Non	30, 40
CAREvent MRI	O-Two Medical Technologies	300, 500, 700	1.0, 0.6	0.05, 0.02	5, 20	5, 10	30, 40
iVent201	GE Healthcare	300, 500, 700	1.0, 0.6	0.05, 0.02	5, 20	5, 10	30, 40
Servo-i	Maquet	300, 500, 700	1, 0, 0.6	0.05, 0.02	5, 20	5, 10	30, 40

* Values in parentheses indicate breathing frequency (breaths/min).
PIP = peak inspiratory pressure

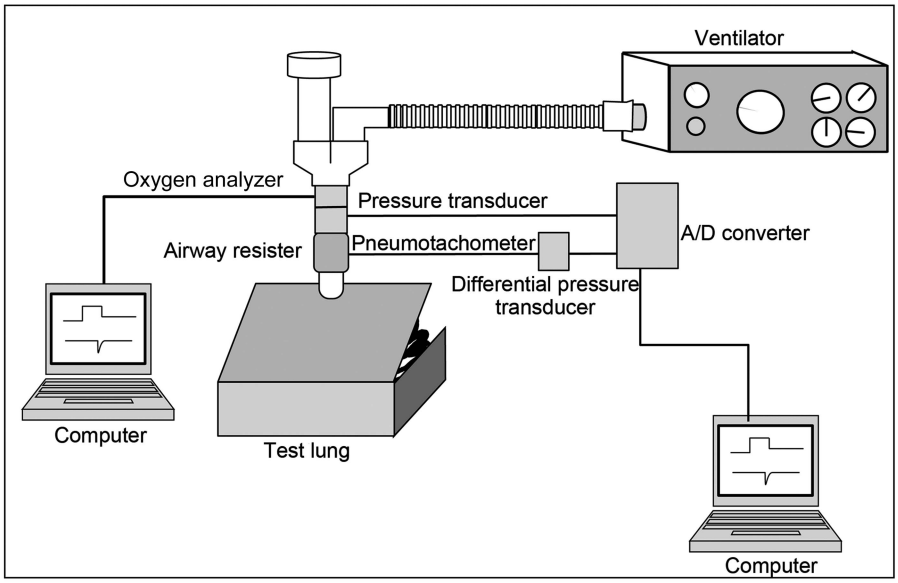

Fig. 1. Experimental setup. Each tested ventilator was connected to the TTL test lung via a ventilator circuit. An oxygen analyzer, a pressure transducer, a pneumotachometer connected to a differential pressure transducer, and an airway-resistance connector were placed between the Y-piece and the test lung. Oxygen concentration was collected directly by a computer; flow and airway-pressure signals were processed through an analog-to-digital (A/D) converter and saved on another computer.

ware (SPSS 11.01, SPSS, Chicago, Illinois). $P < .05$ was considered significant, but we discuss only differences that were both statistically significant and > 10%.

Results

The difference in V_T error was statistically significant among the ventilators. Figure 2 shows percent error of delivered V_T for each ventilator. In general, V_T error was greater at a V_T of 300 mL than at 500 and 700 mL. Delivered V_T was less than set V_T with the Pneupac VR1 and CAREvent MRI and greater with the iVent201 and ParaPAC 200DMRI. Error was negligible with the Servo-i. V_T error was greater at 0.02 L/cm H_2O than at 0.05 L/cm H_2O with the Pneupac VR1 and CAREvent MRI and less with the ParaPAC 200DMRI and Servo-i ($P < .05$). Compliance had no effect on V_T with the iVent201. V_T error was greater at 20 cm H_2O/L/s than at 5 cm H_2O/L/s with the Pneupac VR1 and CAREvent MRI and less with the ParaPAC 200DMRI, iVent201, and Servo-i ($P < .05$) (Fig. 3).

At an F_{IO_2} of 1.0, the difference between set and actual values was small for all ventilators. At 0.6 (or air mix), F_{IO_2} error was 25.3% with the CAREvent MRI (Fig. 4). At 5 and 10 cm H_2O, PEEP error was 42.5% and 17.1% with the CAREvent MRI and −29.2% and −19.0% with the iVent201 (Fig. 5).

At a high-pressure alarm setting of 30 cm H_2O, peak inspiratory pressure was 29 ± 1.3 cm H_2O, and at 40 cm H_2O, it was 38.3 ± 2.1 cm H_2O with all ventilators. The pressure-relief valves worked in each ventilator.

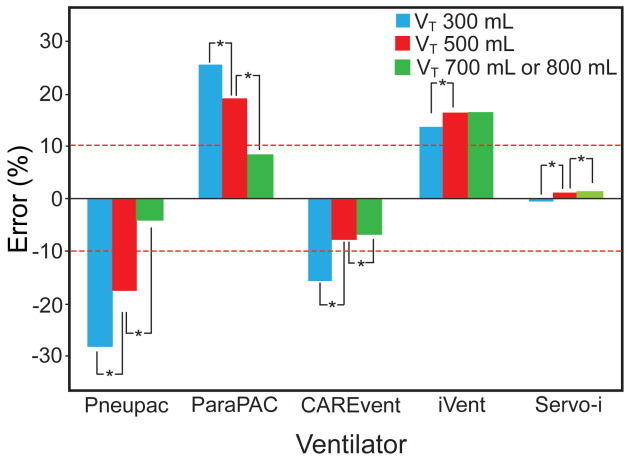

Fig. 2. Tidal volume (V_T) error (% difference between set and actual values) was determined for each ventilator at V_T of 300, 500, and 700 mL. V_T error varied among the ventilators. As V_T increased, V_T error decreased in the Pneupac VR1, ParaPAC 200DMRI, and CAREvent MRI. For V_T of 300 mL, percent error was above ±10% for the Pneupac VR1, ParaPAC 200DMRI, CAREvent MRI, and iVent201. For V_T of 500 mL, percent error was above ±10% for the Pneupac VR1, ParaPAC 200DMRI, and iVent201. For V_T of 700 mL, percent error was above ±10% for the iVent201. Red dashed lines indicate 10% error. * $P < .05$.

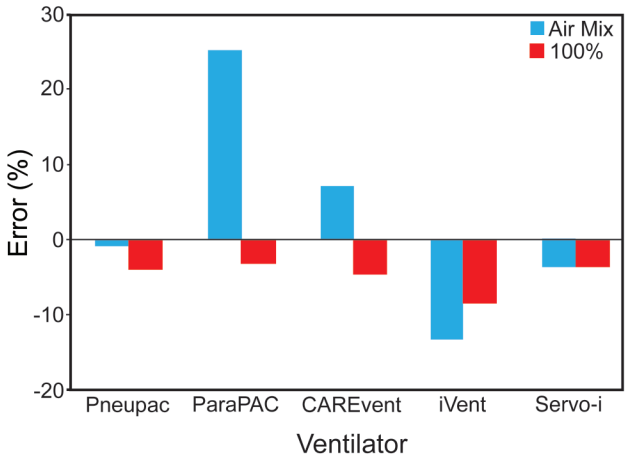

Fig. 4. F_{IO_2} error (% difference between set and actual values) for each ventilator. F_{IO_2} error was small at 1.0. It increased at 0.6 and air-mix settings, especially with the ParaPAC 200DMRI.

Discussion

In this study we tested MRI-compatible ventilators out of the MRI suite. We found that differences in V_T, F_{IO_2}, and PEEP error were statistically significant among the ventilators. Percent V_T error was greater at the low V_T setting. PEEP and F_{IO_2} deviated from the set values, and physicians should carefully observe the respiratory and hemodynamic status of patients during transport and MRI.

In standards laid down by the American Society for Testing and Materials, V_T error within ±10% of the set value is allowable: at V_T = 300 and 500 mL, the Pneupac VR1, ParaPAC 200DMRI, CAREvent MRI, and iVent201 exceeded this margin, and at V_T = 700 mL, the iVent201

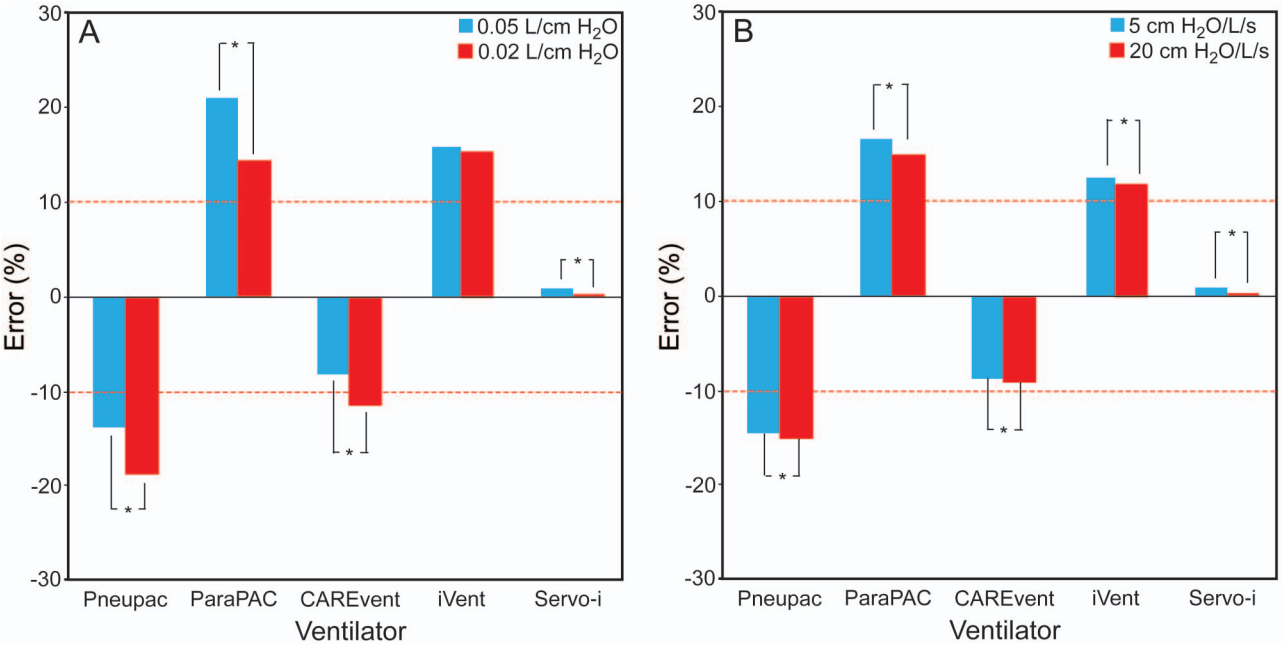

Fig. 3. Effect of compliance and resistance on tidal volume (V_T). A: Effect of compliance. With the Pneupac VR1, ParaPAC 200DMRI, and CAREvent MRI, delivered V_T was smaller at 0.02 L/cm H_2O than at 0.05 L/cm H_2O. Greater error occurred with the Pneupac VR1 and CAREvent MRI than with the ParaPAC 200DMRI. B: Effect of resistance. With the ParaPAC 200DMRI, resistance influenced delivered V_T. Red dashed lines indicate 10% error. * $P < .05$.

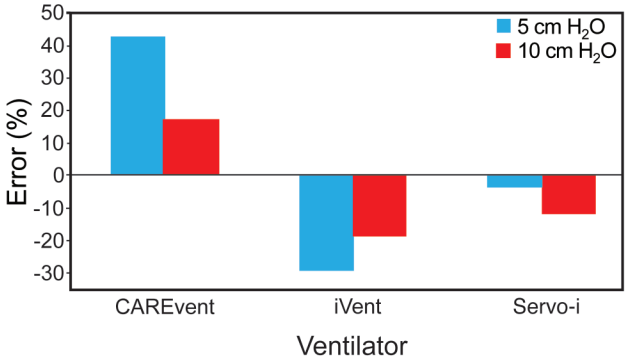

Fig. 5. PEEP error (% difference between set and actual values) for each ventilator. PEEP exceeded the set level with the CAREvent MRI and fell short with the iVent201.

exceeded this margin. Except for the Servo-i, all tested ventilators were portable models. Previous studies[4-8] evaluating the performance of portable ventilators found similarly high V_T errors as in our study. Chipman et al[5] evaluated the performance of 15 transport ventilators, which generally delivered less than set V_T: in test instances, at V_T of 500 and 1,000 mL, error was > 10% in one third of the tests (28/78), and at V_T of 1,000 mL, error was > 10% in half of the tests (32/78). In the present study, with the Pneupac VR1, ParaPAC 200DMRI, and CAREvent MRI, as set V_T increased, V_T error decreased. Flow is also dependent on oxygen supply pressure and lung resistance and compliance, and rather than measuring flow, portable ventilators simply control inspiratory valve opening to control flow (volume). Therefore, a difference between set and actual values is to be expected.

During volume control ventilation, some of the delivered gas volume is compressed in the ventilator circuit. To compensate for this, some ICU ventilators incorporate feedback by measuring the compliance of the circuit and pressure in the airway. Lacking this function, the Pneupac VR1, ParaPAC 200DMRI, and CAREvent MRI delivered lower V_T at a compliance of 0.02 L/cm H_2O compared with 0.05 L/cm H_2O. In volume control mode, higher airway pressure and greater compression volume at a compliance of 0.02 L/cm H_2O resulted in lower V_T compared with 0.05 L/cm H_2O. The Pneupac VR1 and CAREvent MRI delivered lower V_T than set V_T. At low compliance, the difference between their set and actual values was greater than with the ParaPAC. We investigated only volume control mode, and resistance had a small effect on delivered V_T.

We measured V_T with a pneumotachometer and differential pressure transducer using ambient temperature and pressure dry (ATPD). Actual V_T should be measured at body temperature and pressure saturated with water vapor (BTPS). Heat-and-moisture exchangers trap water vapor in expiratory gas, so V_T is underestimated; some ventilators correct V_T to BTPS in screen displays. However, no ventilators evaluated in this study have this function. The Servo-i and iVent201 compensate compression volumes, but this did not influence our measurements. Therefore, we did not convert our ATPD values to BTPS values.

In air-mix mode, F_{IO_2} was 25% higher than set F_{IO_2} with the ParaPAC 200DMRI, and the difference from set F_{IO_2} exceeded ±10% with the iVent201. The Pneupac VR1, ParaPAC 200DMRI, and CAREvent MRI aspirate ambient air using the Venturi effect and do not measure F_{IO_2}. Entrained air volume depends on oxygen flow and cross-sectional area, and oxygen flow is dependent on supply gas pressure and resistance. Consequently, F_{IO_2} is not necessarily constant. These ventilators do not measure F_{IO_2} and do not correct error. Blakeman and Branson[6] reported that F_{IO_2} exceeded ±5% of preset F_{IO_2} with portable ventilators. We found that PEEP error ranged from −29.2 to 42.5%. Chipman et al[5] also reported that several portable ventilators did not maintain PEEP at set values.

As a bench study, our protocols were not performed near operating MRI equipment: it is possible that a strong magnetic field may affect the performance of ventilators. Williams et al[9] tested MRI-compatible ventilators near and away from MRI equipment, however, and reported that performance was similar. We also evaluated only one basic model of each ventilator relying on the manufacturers' quality-control procedures to ensure that all products had the same characteristics, we thus assumed that each was a typical example.

Conclusions

After bench-testing the performance of MRI-compatible ventilators, we found significant differences between set and actual values for V_T, F_{IO_2}, and PEEP. Due to the relatively poor performance of MRI-compatible ventilation equipment used during patient transfer to the MRI suite, we recommend monitoring respiratory and hemodynamic status in all ICU patients. Appropriate vigilance is also essential during ventilation while imaging.

REFERENCES

1. Menon DK, Peden CJ, Hall AS, Sargentoni J, Whitwam JG. Magnetic resonance for the anaesthetist. Part 1. Physical principles, applications, safety aspects. Anaesthesia 1992;47(3):240-255.
2. Peden CJ, Menon DK, Hall AS, Sargentoni J, Whitwam JG. Magnetic resonance for the anaesthetist. Part 2. Anaesthesia and monitoring in MR units. Anaesthesia 1992;47(6):508-517.
3. Zanetta G, Robert D, Guérin C. Evaluation of ventilators used during transport of ICU patients–a bench study. Intensive Care Med 2002; 28(4):443-451.

4. Lyazidi A, Thille AW, Carteaux G, Galia F, Brochard L, Richard JC. Bench test evaluation of volume delivered by modern ICU ventilators during volume-controlled ventilation. Intensive Care Med 2010; 36(12):2074-2080.
5. Chipman DW, Caramez MP, Miyoshi E, Kratohvil JP, Kacmarek RM. Performance comparison of 15 transport ventilators. Respir Care 2007;52(6):740-751.
6. Blakeman TC, Branson RD. Evaluation of 4 new generation portable ventilators. Respir Care 2013;58(2):264-272.
7. Boussen S, Gainnier M, Michelet P. Evaluation of ventilators used during transport of critically ill patients: a bench study. Respir Care 2013;58(11):1911-1922.
8. Blakeman TC, Rodriquez D Jr, Hanseman D, Branson RD. Bench evaluation of 7 home-care ventilators. Respir Care 2011;56(11):1791-1798.
9. Williams EJ, Jones NS, Carpenter TA, Bunch CS, Menon DK. Testing of adult and paediatric ventilators for use in a magnetic resonance imaging unit. Anaesthesia 1999;54(10):969-974.