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Performance of ventilators for noninvasive positive-pressure ventilation in children

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ABSTRACT: The aim of the present study was to evaluate the performance characteristics of all the ventilators proposed for home noninvasive positive-pressure ventilation in children in France.

The ventilators (one volume-targeted, 12 pressure-targeted and four dual) were evaluated on a bench which simulated six different paediatric ventilatory patterns. For each ventilator, the quality of the inspiratory and expiratory trigger and the ability to reach and maintain the preset pressures and volumes were evaluated with the six patient profiles.

The performance of the ventilators showed great variability, and depended upon the type of trigger (flow or pressure), type of circuit and patient profile. Differences were observed between the preset and measured airway pressure and between the tidal volume measured by the ventilator and on the bench. Leaks were associated with an inability to detect the patient's inspiratory effort or autotriggering. No single ventilator was able to adequately ventilate the six paediatric profiles. Only a few ventilators were able to ventilate the profiles simulating the youngest patients.

A systematic paediatric bench evaluation is recommended for every ventilator proposed for home ventilation, in order to detect any dysfunction and guide the choice of the appropriate ventilator for a specific patient.

KEYWORDS: Bench study, child, lung model, pressure support, trigger, volume-targeted ventilation

Noninvasive positive-pressure ventilation (NPPV) is increasingly used at home in children [1]. NPPV may improve respiratory failure in children with neuromuscular disease [2, 3], upper airway obstruction and sleep apnoea [4], and lung diseases such as cystic fibrosis [5]. These diseases concern both infants and older children, which implies that the ventilator should be able to adapt to a broad range of patient demands. Children with respiratory failure, especially the youngest ones, may develop extreme breathing patterns, which may represent a challenge for a ventilator [6]. Indeed, home ventilators may not be able to adequately synchronise with patient respiratory effort [7, 8], leak compensation may be insufficient, and the triggers of assist modes and alarms are not always adapted for young children. This is explained by the fact that most ventilators have not been specifically developed for paediatric patients. However, in practice, the clinician has to deal with the available devices.

Although some studies have tested or compared home ventilators in young patients with cystic fibrosis [7, 8] or upper airway obstruction [6], no study has evaluated different types of ventilator in children with various causes of chronic respiratory insufficiency. In France, 17 ventilators are proposed for home ventilation in children. Thus, the choice of the most appropriate ventilator for a specific patient is a real challenge for the clinician. Indeed, the testing of several ventilators in every single patient is unrealistic in practice.

The aim of the present study was to evaluate the performance of the 17 ventilators available for home ventilation in France with the most common paediatric profiles, namely neuromuscular disease, upper airway obstruction and cystic fibrosis. In order to do this, a bench lung model that simulated the mechanical respiratory characteristics and pattern of breathing of six typical paediatric patient profiles was used.

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MATERIALS AND METHODS

Patient profiles

In the present authors' experience, approximately a third of the children treated with NPPV at home have neuromuscular diseases, a third upper airway obstruction and a final third lung diseases or other causes of chronic hypercapnic respiratory insufficiency [1]. Thus, six patient profiles representing ~90% of patient profiles experienced were selected from the present authors' NPPV cohort (table 1).

During routine initiation of NPPV and follow-up, breathing pattern at baseline, respiratory mechanics and respiratory output were recorded using a pneumotachograph (Fleisch No. 3; Fleisch, Lausanne, Switzerland) and a catheter-mounted pressure transducer system with two integral transducers (Gaeltec, Dunvegan, UK). Breathing pattern at baseline, *i.e.* when the patient was not connected to a ventilator and breathing spontaneously, was inferred by measuring the patient flow rate. Tidal volume (V_T) and inspiratory time (t_I) were directly deduced from this flow tracing (table 1).

The patient's respiratory mechanics were inferred when the patient was connected to the ventilator *via* measurement of transdiaphragmatic pressure and oesophageal pressure (P_{oes}) as previously described [5]. Briefly, dynamic lung compliance ($C_{L,dyn}$) was calculated as the ratio of V_T to the P_{oes} difference between the beginning and end of inspiration during quiet breathing. Individual values indicated in table 1 were averaged on the basis of 10–20 consecutive cycles during air breathing.

Airway and lung resistance (R_{rs}) was calculated according to the following formula, based on the technique of MEAD and WHITTENBERGER [9].

$$R_{rs}=[(P_{oes,0}-P_{oes})-(V/C_{L,dyn})]/V' \quad (1)$$

$P_{oes,0}$ is P_{oes} at the start of inspiratory flow, V is instantaneous volume, $C_{L,dyn}$ is calculated for the same breath and V' is instantaneous airflow. Mean values over the inspiration were used as estimates of inspiratory R_{rs} (table 1).

The analysis of the patients' profiles was approved by the ethics committee of Saint Antoine University Hospital (Paris, France), and patients and parents gave their informed consent.

Ventilator testing

In total, 17 ventilators were tested: 12 pressure-targeted, one volume-targeted and four capable of both modes (table 2). Each ventilator was tested with the six different patient profiles and with the recommended circuits. When assisted controlled ventilation (ACV) and pressure-support (PS) ventilation (PSV) were available, both modes were tested.

The ventilator setting (targeted pressure or volume and positive end-expiratory pressure (PEEP)) was different for each patient profile (table 1). The first two patients, a 4-yr-old male with spinal muscular atrophy and a 17-yr-old male with Duchenne muscular dystrophy, had neuromuscular disease. Since both ACV and PSV may be used in such patients, ventilators able to deliver one or both modes were tested. For patient No. 3, with cystic fibrosis, ventilators able to deliver PSV and/or ACV were tested. For these first three patients, PSV or ACV with zero end-expiratory pressure (ZEEP) was

TABLE 1 Patient profiles and ventilatory modes used for the bench lung model study[#]

Patient no.	Pathology	Age yrs	Weight kg	Vt mL	t_I s	$C_{L,dyn}$ L·cm^{-1} H_2O	R_{rs}/R_p cmH_2O·L^{-1}·s	$P_{0.1}$ cmH_2O[¶]	$V_{0.1}$ mL[¶]	$V'_{0.1}$ mL·s^{-1}[¶]	Ventilatory mode[+]
1	Spinal muscular amyotrophy	4	13	150	1.3	0.038	52/50	0.94	5.8	71	PSV10 ZEEP; ACV250 ZEEP
2	Duchenne muscular dystrophy	19	70	293	0.9	0.024	17/20	2.8	9.5	142	PSV16 ZEEP; ACV500 ZEEP
3	Cystic fibrosis	14	27	188	1.1	0.019	57/50	2.5	11.0	135	PSV16 ZEEP; ACV500 ZEEP
4	Laryngomalacia	0.25	4	18	1.0	0.024	200[§]	0.4	1.3	17	PSV14 PEEP8
5	Vocal cord paralysis	4	12	250	1.3	0.064	6/5	1.4	14.7	180	PSV14 PEEP8
6	Central apnoea	13	42	296	1.1	0.153	7/5	4.3	19.7	273	PSV12 ZEEP

V_T: tidal volume; t_I: inspiratory time; $C_{L,dyn}$: dynamic lung compliance; R_{rs}: airway and lung resistance; R_p: resistance of the parabolic airway resistor used to simulate lung resistance; $P_{0.1}$: inspiratory airway occlusion pressure 0.1 s after initiation of spontaneous breath; $V_{0.1}$: inspired volume 0.1 s after initiation of spontaneous breath; $V'_{0.1}$: inspiratory flow 0.1 s after initiation of spontaneous breath; PSV: pressure-support ventilation; ZEEP: zero end-expiratory pressure; PEEP: positive end-expiratory pressure; ACV: assisted controlled ventilation. [#]: respiratory mechanics measured during wakefulness; [¶]: measured on the bench test; [+]: values shown represent pressure support in cmH_2O for PSV, V_T in mL for ACV, and PEEP in cmH_2O; [§]: R_p could not be measured in this patient.

TABLE 2 Ventilators tested

	Manufacturer	Mode	Circuit	Trigger	ZEEP	CPAP	Humidifier	Remarks
Elisée 150	ResMed[#]	P/V	S/D	NCTT	Yes	No	No	Adult/child
Eole 3	ResMed[#]	V	S/D	*V′*/*P*	Yes	No	No	Not newborns
GK 425ST	Tyco Healthcare[¶]	P	S+leak	NCTT	No	Yes	Yes	>30 kg
Harmony 2	Respironics France[+]	P	S+leak	NCTT	No	Yes	Yes	
iSleep 22	ResMed[#]	B	S+leak	NCTT	No	Yes	Yes	
KnightStar 330	Tyco Healthcare[¶]	B	S+leak	NCTT	No	Yes	No	>30 kg
Legendair	Airox[§]	P/V	S	NCTT	Yes	No	No	Adult/child
NEFTIS 2	Taema[ƒ]	P/V	S	NCTT	Yes	No	No	Invasive/NPPV; adult/child
Smartair+	Airox[§]	P	S/S+leak	NCTT	Yes	No	No	Invasive/NPPV
Synchrony	Respironics France[+]	P	S+leak	NCTT	No	Yes	No	
Synchrony 2	Respironics France[+]	P	S+leak	NCTT	No	Yes	Yes	>30 kg
Vivo 40	Breas Medical[#]	P	S+leak	NCTT	No	Yes	Yes	Adult/child
VPAP III ST	ResMed[#]	P	S+leak	NCTT	No	Yes	Yes	
VPAP III ST-A	ResMed[#]	P	S+leak	NCTT	No	Yes	Yes	
VS Integra	ResMed[#]	P	S/S+leak	NCTT	No:S+leak; yes:S	No	No	Adult/child
VS Serena	ResMed[#]	P	S+leak	NCTT	No	No	No	Adult/child
VS Ultra	ResMed[#]	P/V	S/D/S+leak	*V′*/*P*	No:S+leak; yes:S/D	No	No	Adult/child

ZEEP: zero end-expiratory pressure: CPAP: continuous positive airway pressure: P: pressure-limited mode; V: volume-targeted mode; B: bilevel positive pressure ventilation; S: simple circuit with expiratory valve; D: double circuit; S+leak: simple circuit with leak; NCTT: no choice of trigger type; *V′*: flow; *P*: pressure; NPPV: noninvasive positive-pressure ventilation. [#]: Saint Priest, France; [¶]: Elancourt, France; [+]: Carquefou, France; [§]: Pau, France; [ƒ]: Anthony, France.

chosen because of the absence of or a low (<2 cmH_2O) intrinsic PEEP [5, 10]. Patient No. 4 was an infant with laryngomalacia in whom only ventilators able to deliver PS with PEEP were tested. PSV with PEEP ventilators were tested in patient No. 5, who had obstructive sleep apnoea due to vocal cord paralysis. All of the PSV ventilators able to deliver ZEEP were tested in patient No. 6, who had central apnoea.

All ventilators were studied using their most sensitive inspiratory trigger that did not induce autotriggering. When possible, the highest inspiratory flow was used. For the majority of the ventilators, the expiratory trigger was set automatically. In four ventilators (GK 425ST, KnightStar 330, Vivo 40 and VPAP III ST-A), it was possible to modify the sensitivity of the expiratory trigger. In such cases, the most sensitive level that did not induce a t_I inferior to the spontaneous t_I was used. Where available on the same ventilator, pressure- and flow-triggering were tested. In the case of an optional integrated humidification system, the ventilator was tested with and without the humidification system. For all of the ventilators, the most recent model (year 2006) was used.

Experimental bench study

Each ventilator tested was connected *via* its standard circuit to the first, testing, chamber of a two-chamber Michigan test lung (MII Vent Aid TTL; Michigan Instruments, Grand Rapids, MI, USA; fig. 1). The second, driving, chamber of the test lung was connected to a flow-rate generator that could produce various waveforms previously stored in a microcomputer. The two chambers were physically connected to each other *via* a small metal component that permitted the driving chamber to lift the testing chamber. The flow-rate generator, developed by INSERM Unit 841 (Créteil, France) as previously described, was built by associating pressurised air, flow-rate measurement and a servo-valve driven by a microcomputer [11]. This permits continuous adjustment of the servo-valve in order to produce the desired flow for each patient profile, as indicated in the Patient profiles section. Moreover, in order to simulate the mechanical characteristics of the respiratory system of each patient, the compliance of the testing chamber was adjusted and a resistance added between the testing chamber and the ventilator tested. The compliance of the testing chambers (compliance of the respiratory system; C_{rs}) was set according to the following formula, where C_W is the theoretical chest wall compliance, which represents ~4% of the patient's predicted vital capacity per cmH_2O, and C_L is the lung compliance corresponding to the patient's $C_{L,dyn}$.

$$1/C_{rs}=1/C_W+1/C_L \quad (2)$$

The resistance was a parabolic airway resistor, Pneuflo® airway resistor Rp5, Rp20, Rp50 or Rp200 (Michigan Instruments). For each profile, the resulting breathing effort generated in the bench test was characterised by the inspiratory airway occlusion pressure at 0.1 s ($P_{0.1}$), and by the inspiratory volume and flow 0.1 s after initiation of a spontaneous breath ($V_{0.1}$ and $V'_{0.1}$, respectively; table 1). $P_{0.1}$ was inferred when the ventilator under test and its circuit (fig. 1) were replaced by a rigid stopper, and $V_{0.1}$ and $V'_{0.1}$ were inferred when the lung test was opened to the atmosphere. A leak valve was added to simulate leaks that could occur through a mask during NPPV, which permitted the testing of an increasing leak.

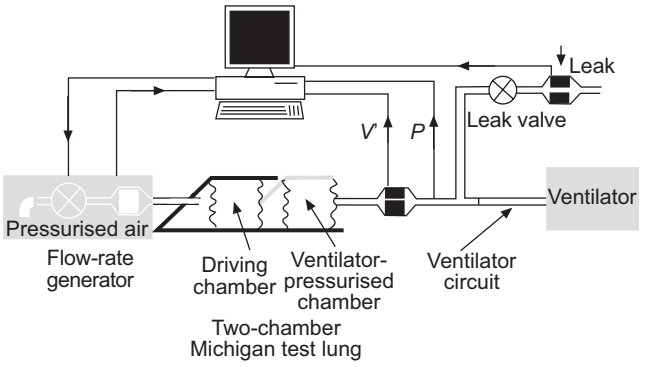

FIGURE 1. Lung bench model used for the study. *V'*: flow; *P*: pressure.

Airway pressure (P_{aw}) and flow were measured at the end of the ventilator circuit using, respectively, a pressure differential transducer (Validyne DP 45±56 cmH_2O; Validyne Northridge, CA, USA) and a pneumotachograph (Fleisch No. 2) associated with a pressure differential transducer (Validyne DP 45±3.5 cmH_2O). The leak flow was measured using a second pneumotachograph. Calibration of pressure and flow was performed before each test. Signals were digitised at 200 Hz by an analogue/digital system (MP100; Biopac Systems, Goleta, CA, USA) and recorded on a microcomputer for further analysis.

As is generally the case, the following parameters were computed from each pressure and/or flow trace: PEEP, PS for PSV, measured V_T ($V_{T,m}$), and V_T indicated by the ventilator ($V_{T,V}$). The sensitivity of the inspiratory trigger was evaluated from the trigger time delay (Δt; time between onset of inspiratory effort and point of minimum P_{aw}) and the trigger pressure (ΔP; pressure swing between baseline pressure and minimum P_{aw}) [7]. The sensitivity of the expiratory trigger was evaluated as the difference between the patient's t_I during spontaneous breathing and the t_I during NPPV. The pressurisation slope was calculated for 150 ms from the time of minimum P_{aw}. Each parameter was averaged on the basis of 30 respiratory cycles.

In order to facilitate interpretation of the results and guide the reader, the performances of the ventilators are presented qualitatively as follows. The inspiratory trigger was considered appropriate for a Δt of ⩽100 ms and ΔP of ⩽ -1.0 cmH_2O [12], acceptable for a Δt of 100–150 ms and ΔP of -1.5–0 cmH_2O or a Δt of 0–150 ms and ΔP of -1.5– -1.0 cmH_2O, and inappropriate if the ventilator did not detect the inspiratory effort or in the case of autotriggering. The coping of the ventilator with leaks was ranked as follows: 1) relatively insensitive to a leak (no triggering or autotriggering for a leak of ⩾40 $L \cdot min^{-1}$); 2) moderately sensitive to a leak (no triggering or autotriggering for a leak of 10–40 $L \cdot min^{-1}$); and 3) very sensitive to a leak (no triggering or autotriggering for a leak of ⩽10 $L \cdot min^{-1}$). The performance of each ventilator is also presented qualitatively as follows: appropriate for a $V_{T,m}$ of less than the required V_T±10% for ACV, and for a measured PS (PS_m) of less than the required PS±10% and pressurisation slope of ⩾60 $cmH_2O \cdot s^{-1}$ for PSV; acceptable for a $V_{T,m}$ of less than the required V_T±15% for ACV, and a PS_m of less than the required PS±15% and pressurisation slope of ⩾40 $cmH_2O \cdot s^{-1}$ for PSV; and inappropriate for nondetection of the inspiratory effort or autotriggering, or for a $V_{T,m}$ of ⩾V_T±15% for ACV, or a PS_m of at least the required PS±15% and pressurisation slope <40 $cmH_2O \cdot s^{-1}$ for PSV.

RESULTS

Except in three cases, Smartair+ in the patient with cystic fibrosis (profile No. 3), Vivo 40 in the patient with vocal cord paralysis (profile No. 5), and VS Ultra double-circuit pressure trigger in the patient with central apnoea (profile No. 6), very close results were found with and without the humidification system. Therefore, the results are presented as the means obtained with and without humidification.

The complete data concerning the performance of each ventilator for the six different patient profiles are given in the supplementary material (online tables 1–6). For the patient with spinal muscular atrophy, all of the seven ventilators that had a compatible mode had inappropriate triggers (table 3). For the adolescent with Duchenne muscular dystrophy, only two ventilators, Eole 3 with flow trigger and Legendair, had an appropriate inspiratory trigger in the ACV mode. However, the Eole 3 was very sensitive, and the Legendair moderately sensitive, to leaks. Of the five other ventilators that had a compatible mode, all had an inappropriate trigger. For the patient with cystic fibrosis, only four ventilators had an appropriate trigger: Eole 3 with flow trigger; Legendair in both modes; Smartair+ with simple circuit; and VS Ultra in PSV mode with pressure trigger and double circuit, and in ACV mode with simple circuit. The VS Ultra had an acceptable trigger when in PSV mode with simple circuit and in ACV mode with double circuit and pressure trigger. However, the Elisée 150, NEFTIS 2 and VS Integra all had inappropriate triggers. None of the 16 PSV ventilators were able to detect the inspiratory effort of the infant with laryngomalacia. For the patient with vocal cord paralysis, four ventilators had an appropriate trigger: iSleep 22, KnightStar 330, VS Integra with simple circuit and VS Serena. However, these ventilators were either moderately sensitive (iSleep 22 and VS Serena) or very sensitive (KnightStar 330 and VS Integra with simple circuit) to leaks. For this patient profile, eight ventilators had an acceptable trigger: GK 425ST, Harmony 2, Legendair, NEFTIS 2, Synchrony, Synchrony 2, VPAP III ST-A and VS Ultra with simple circuit or double circuit with pressure trigger. Only four ventilators had an inappropriate trigger: Elisée 150, Smartair, Vivo 40 and VPAP III ST-A. Four ventilators were relatively insensitive to leaks (GK 425ST, Harmony 2, Synchrony, and Synchrony 2) and three were moderately sensitive to leaks (iSleep 22, VPAP III ST-A and VS Serena), the other five being very sensitive to leaks. None of the six ventilators that had a compatible mode had an appropriate trigger for the patient with central apnoea, although three ventilators had an acceptable trigger: Legendair, Smartair with simple circuit and VS Ultra. However, none of these ventilators coped adequately with leaks. The Elisée 150, NEFTIS 2 and VS Integra had inappropriate triggers.

The quality of the expiratory triggers is presented in the supplementary material (online table 7). The major observation is that the performance of the expiratory triggers varies according to ventilator and also to patient profile. Only the KnightStar 330 and the Legendair were able to detect the

TABLE 3 Trigger performances of the ventilators according to the six patient profiles

	Spinal muscular amyotrophy	Duchenne muscular dystrophy	Cystic fibrosis	Laryngomalacia	Vocal cord paralysis	Central apnoea
Mode	PSV/ACV	PSV/ACV	PSV/ACV	PSV/PEEP	PSV/PEEP	PSV/ZEEP
Elisée 150	Inappropriate	Inappropriate	Inappropriate	Inappropriate	Inappropriate	Inappropriate
Eole 3	Inappropriate	Acceptable ACV$^{\#}$ (3)	Appropriate ACV$^{\#}$ (3)	NCM	NCM	NCM
GK 425ST	NCM	NCM	NCM	Inappropriate	Acceptable (1)	NCM
Harmony 2	NCM	NCM	NCM	Inappropriate	Acceptable (1)	NCM
iSleep 22	NCM	NCM	NCM	Inappropriate	Appropriate (2)	NCM
KnightStar 330	NCM	NCM	NCM	Inappropriate	Appropriate (3)	NCM
Legendair	Inappropriate	Acceptable ACV (2)	Appropriate PSV (1); ACV (3)	Inappropriate	Acceptable (3)	Acceptable (3)
NEFTIS 2	Inappropriate	Inappropriate	Inappropriate	Inappropriate	Acceptable (3)	Inappropriate
Smartair+	Inappropriate	Inappropriate	Appropriate¶ (1)	Inappropriate	Inappropriate	Acceptable¶ (3)
Synchrony	NCM	NCM	NCM	Inappropriate	Acceptable (1)	NCM
Synchrony 2	NCM	NCM	NCM	Inappropriate	Acceptable (1)	NCM
Vivo 40	NCM	NCM	NCM	Inappropriate	Inappropriate	NCM
VPAP III ST	NCM	NCM	NCM	Inappropriate	Inappropriate	NCM
VPAP III ST-A	NCM	NCM	NCM	Inappropriate	Acceptable (2)	NCM
VS Integra	Inappropriate	Inappropriate	Inappropriate	Inappropriate	Appropriate¶ (3)	Inappropriate
VS Serena	NCM	NCM	NCM	Inappropriate	Appropriate (2)	NCM
VS Ultra	Inappropriate	Inappropriate	Acceptable PSV¶/ACV^{+} (3); appropriate PSV^{+}/ACV¶ (3)	Inappropriate	Acceptable$^{\P,+}$ (3)	Acceptable^{+} (2)

The inspiratory trigger was considered appropriate for a trigger time delay (Δt) of $\leqslant$100 ms and trigger pressure (ΔP) of $\leqslant$ -1.0 cmH_2O, acceptable for a Δt of 100–150 ms and ΔP of -1.5–0 cmH_2O or a Δt of 0–150 ms and ΔP of -1.5– -1.0 cmH_2O, and inappropriate if the ventilator did not detect the inspiratory effort or in the case of autotriggering. The coping of the ventilator with leaks was ranked as follows: 1) relatively insensitive to a leak (no triggering or autotriggering for a leak of $\geqslant$40 $L \cdot min^{-1}$); 2) moderately sensitive to a leak (no triggering or autotriggering for a leak of 10–40 $L \cdot min^{-1}$); and 3) very sensitive to a leak (no triggering or autotriggering for a leak of $\leqslant$10 $L \cdot min^{-1}$). PSV: pressure-support ventilation; ACV: assisted controlled ventilation; PEEP: positive end-expiratory pressure; ZEEP: zero end-expiratory pressure; NCM: no compatible mode. $^{\#}$: flow trigger; ¶: simple circuit; $^{+}$: double-circuit pressure trigger.

expiratory effort of patient No. 4, the infant with laryngomalacia. The expiratory trigger of the Elisée 150 was good in patient No. 2 (Duchenne muscular dystrophy) but much less so in patients No. 3 (cystic fibrosis) and 5 (vocal cord paralysis).

Concerning the performance of the ventilators, for patient No. 1 with spinal muscular atrophy, only the Elisée 150 in the ACV mode with a simple circuit had an appropriate performance (table 4). The performance of the NEFTIS 2 and VS Ultra with a double circuit and flow trigger were acceptable, while four ventilators had an inappropriate performance (Eole 3, Legendair, Smartair+, and VS Integra). The Elisée 150, the Legendair in the ACV mode, and the VS Ultra in the PSV mode with a simple circuit or a double circuit with flow trigger had an appropriate performance. The performance of the VS Ultra in the ACV mode with a double circuit and flow trigger was acceptable, whereas the performance of the NEFTIS 2, the Smartair+ and the VS Integra was inappropriate. For the patient with cystic fibrosis, only three ventilators had an appropriate performance: Eole 3, NEFTIS 2, and VS Ultra with the two modes with a simple circuit or a double circuit with flow trigger. The KnightStar 330 was the only ventilator having an acceptable performance in the infant with laryngomalacia. For the patient with vocal cord paralysis, two ventilators had an acceptable performance: VPAP III ST-A and VS Ultra with a simple circuit or with a double circuit and pressure trigger. All the other devices with a compatible mode had inappropriate performances. For the patient with central apnoea, the Elisée 150 with a double circuit and the VS Ultra with a double circuit and flow trigger had appropriate performances, whereas the other four ventilators that had a compatible mode had inappropriate performances.

DISCUSSION

The current study is the first to provide a bench test evaluation of the performance of a broad range of home ventilators, none of which were primarily developed for children, for six different paediatric patient profiles according to a strict protocol. The major findings of the present study can be summarised as follows: 1) no ventilator is perfect and able to adequately ventilate the six different patient profiles; 2) the performance of the ventilators was very heterogeneous and depended upon the type of trigger and circuit and, most importantly, upon the characteristics of the patient; and 3) the sensitivity of the inspiratory triggers of most of the ventilators was insufficient for infants.

Paediatric specificities

The present study confirms the limitations of the ventilators currently available for home ventilation in children. Numerous ventilators were unable to respond adequately to the patient's demands. Several paediatric specificities may explain these

TABLE 4 Performance of the ventilators according to the six patient profiles

	Spinal muscular amyotrophy	Duchenne muscular dystrophy	Cystic fibrosis	Laryngomalacia	Vocal cord paralysis	Central apnoea
Mode	PSV/ACV	PSV/ACV	PSV/ACV	PSV/PEEP	PSV/PEEP	PSV/ZEEP
Elisée 150	Appropriate ACV[#]	Appropriate	Acceptable ACV[¶]	Inappropriate	Inappropriate	Appropriate[¶]
Eole 3	Inappropriate	Inappropriate	Appropriate ACV[+] (1)	NCM	NCM	NCM
GK 425ST	NCM	NCM	NCM	Inappropriate	Inappropriate	NCM
Harmony 2	NCM	NCM	NCM	Inappropriate	Inappropriate	NCM
iSleep 22	NCM	NCM	NCM	Inappropriate	Inappropriate	NCM
KnightStar 330	NCM	NCM	NCM	Acceptable	Inappropriate	NCM
Legendair	Inappropriate	Appropriate ACV	Inappropriate	Inappropriate	Inappropriate	Inappropriate
NEFTIS 2	Acceptable	Inappropriate	Appropriate	Inappropriate	Inappropriate	Inappropriate
Smartair+	Inappropriate	Inappropriate	Inappropriate	Inappropriate	Inappropriate	Inappropriate
Synchrony	NCM	NCM	NCM	Inappropriate	Inappropriate	NCM
Synchrony 2	NCM	NCM	NCM	Inappropriate	Inappropriate	NCM
Vivo 40	NCM	NCM	NCM	Inappropriate	Inappropriate	NCM
VPAP III ST	NCM	NCM	NCM	Inappropriate	Inappropriate	NCM
VPAP III ST-A	NCM	NCM	NCM	Inappropriate	Acceptable	NCM
VS Integra	Inappropriate	Inappropriate	Inappropriate	Inappropriate	Inappropriate	Inappropriate
VS Serena	NCM	NCM	NCM	Inappropriate	Inappropriate	NCM
VS Ultra	Acceptable[§,ƒ]	Appropriate PSV[#,§,ƒ]; acceptable ACV[§,ƒ]	Appropriate PSV ACV[#,##]; acceptable ACV[§,ƒ]	Inappropriate	Acceptable[#,##]	Appropriate[##]

The performance of each ventilator is presented qualitatively as follows: appropriate for a tidal volume (V_T) measurement ($V_{T,m}$) of less than the required $V_T \pm 10\%$ for assisted controlled ventilation (ACV), and for a pressure support (PS) measurement (PS_m) of less than the required $PS \pm 10\%$ and pressurisation slope of $\geqslant 60$ $cmH_2O \cdot s^{-1}$ for PS ventilation (PSV); acceptable for a $V_{T,m}$ of less than the required $V_T \pm 15\%$ for ACV, and a PS_m of less than the required $PS \pm 15\%$ and pressurisation slope of $\geqslant 40$ $cmH_2O \cdot s^{-1}$ for PSV; and inappropriate for nondetection of the inspiratory effort or autotriggering, or for a $V_{T,m}$ of $\geqslant V_T \pm 15\%$ for ACV, or a PS_m of at least the required $PS \pm 15\%$ and pressurisation slope <40 $cmH_2O \cdot s^{-1}$ for PSV. The coping of the ventilator with leaks was ranked as follows: 1) relatively insensitive to a leak (no triggering or autotriggering for a leak of $\geqslant 40$ $L \cdot min^{-1}$). PEEP: positive end-expiratory pressure; ZEEP: zero end-expiratory pressure; NCM: no compatible mode. [#]: simple circuit; [¶]: double circuit; [+]: flow trigger; [§]: double circuit flow trigger; [ƒ]: ZEEP=1.4 cmH_2O; [##]: double circuit pressure trigger.

difficulties. For example, the patient's inspiratory effort may be too low, or lower than that of adults, reducing the ability of the ventilator to detect the onset of inspiration. For the six patient profiles, $P_{0.1}$ in the lung model ranged 0.4–4.3 cmH_2O. This is in agreement with values reported in the literature for adults [13]. A recent study observed that inspiratory effort, evaluated by $P_{0.1}$, was higher in children with neuromuscular disease than in healthy controls [14]. However, when each patient's $P_{0.1}$ was assessed in terms of the number of ventilators detecting the patient's inspiratory effort, it was observed that the patients who exhibited the lowest $P_{0.1}$ were also those in whom the majority of the ventilators were unable to detect the patient's inspiratory effort. Indeed, only 39% of the ventilators were able to detect the inspiratory effort of patient No. 1 (online table 1), who had a $P_{0.1}$ of 0.94 cmH_2O, and only 9% of the ventilators were able to detect the inspiratory effort of patient No. 4 (online table 4), who had a $P_{0.1}$ of 0.4 cmH_2O. This suggests that the inspiratory effort generated by the youngest children may be too small to be detected by the majority of ventilators. Moreover, these two patients also exhibited the lowest $V_{0.1}$ and $V'_{0.1}$ during spontaneous breathing (with $V_{0.1}$ of 5.8 and 1.3 mL, and $V'_{0.1}$ of 17 and 17 $mL \cdot s^{-1}$, for patients No. 1 and 4, respectively). This implies that a ventilator with a trigger based upon a flow signal should be able to detect a flow and/or volume inferior to these values in order to generate an adequate Δt. In practice, the use of a high back-up rate, *i.e.* equivalent to or two or three breaths below the patient's spontaneous respiratory frequency, may overcome the problems associated with an inadequate inspiratory trigger. Such a setting is recommended for patients with neuromuscular disease [15].

The patient with central apnoea should, theoretically, have been ventilated using a controlled mode. However, such patients may take some spontaneous breaths. Thus, in order to increase the comfort of NPPV and favour the synchronisation of the patient with the ventilator, a spontaneous mode with a back-up rate slightly below the spontaneous respiratory frequency of the patient may be used, permitting the evaluation of the inspiratory trigger in this patient.

These limitations of the ventilators observed in the present study with simulated paediatric patterns were not completely unexpected, since few devices have been specifically developed for children. In addition, the majority of the manufacturers (12 out of 17) do not implicitly recommend ventilation of the youngest children with their ventilator (with the ventilators being denoted adult/child, not for newborn, or >30 kg). The quality of the inspiratory triggers may also limit the performance of ventilators. Nevertheless, due to the lack of information disclosed by the manufacturers concerning the

principle and algorithms used for the inspiratory trigger, it is difficult to understand why one ventilator seems to exhibit a better trigger than another. With a classical pressure trigger, a closed system is mandatory in order to facilitate the generation of a differential pressure. For example, in the case of the Eole 3 pressure trigger, no large decrease in P_{aw} was observed during the patient's inspiratory effort while an inspiratory flow signal was detected. This confirms that it is an open system, which is one explanation for the lack of detection of the inspiratory effort observed with this ventilator. With a trigger based upon flow signal, the system should be open. One of the major problems of such a trigger is the take-up of the leak. Nevertheless the present results do not suggest that a simple circuit plus leak permitted a better or worse inspiratory trigger than ventilation without leak (with a simple or double circuit). In the case of a flow trigger, the ventilator should be able to detect very low flows, especially in young children who have the smallest V_T. Significant differences with regard to the expiratory triggers were also observed. These results are in agreement with clinical results, which showed that the sensitivity of the expiratory triggers may be insufficient for infants requiring NPPV for severe upper airway obstruction [6].

Characteristics of the ventilators

Ventilators are becoming more sophisticated and tend to continuously integrate new options and measures. A large number of ventilators are able to deliver different ventilatory modes, such as PSV, with or without PEEP, as well as ACV. Different circuits (simple, double or leak) and triggers (pressure or flow) may be available on the same ventilator. The present study clearly shows that the performance of a ventilator may vary according to the ventilatory mode or type of trigger and circuit. Indeed, the quality of the inspiratory trigger varied among the different ventilators, and also for a specific ventilator, according to patient profile. For example, the Δt of the NEFTIS 2 was shorter in patient No. 6, who showed high inspiratory effort, than in patient No. 1, who showed low inspiratory effort (0.15 *versus* 0.28 s, respectively; online tables 1 and 6). It is important that the clinician who chooses the device is aware of these differences, which are rarely specified by the manufacturer.

Some ventilators, such as the Legendair, showed a low pressurisation slope and stability index, which signifies that the ventilator is not able to reach the preset pressure within a minimal time frame. Most ventilators measure physiological variables, such as V_T or P_{aw}. Significant differences were observed for almost all of the ventilators between the results shown on the ventilator and the values measured on the bench. This may be explained by the fact that most of these variables are estimated by software incorporated inside the ventilator. Since NPPV is leak ventilation, the $V_{T,V}$ represents the volume of air generated by the device. On the bench, the $V_{T,m}$ was measured by a pneumotachograph inserted between the circuit and the interface. Thus, this measure was closer to the patient and more accurately reflects the V_T received by the patient in the case of calibrated leak ventilation. However, differences between the V_T set on the ventilator and the V_T measured by the ventilator and by a pneumotachograph have also been observed previously with other ventilatory modes [16]. It should be noted that less discrepancy was observed for P_{aw}.

The ability of a ventilator to compensate for additional leaks is important in the case of NPPV. Therefore, the effect of an additional leak in the inspiratory circuit was tested for every ventilator. Most of the ventilators were unable to cope with additional leaks, which resulted in autotriggering or an inability to detect the patient's inspiratory effort.

Advantages and limitations of the study

The responses of several devices to identical mechanical properties of the respiratory system and patterns of inspiratory flow contour were compared, which is not possible in a clinical study given the variability of these respiratory parameters. In addition, given the number of ventilators available for testing, it would be unreasonable to ask children to perform such a study.

One limitation of the bench is that the resistance added by the test system may be more representative of upper airway obstruction, as encountered in the patients with laryngomalacia and vocal cord paralysis, than small airway disease, such as encountered in the patient with cystic fibrosis.

Another limitation of the present study was that the six patients were recorded during wakefulness and not during sleep. Sleep may be associated with both upper airway and inspiratory effort instability. Thus, the mechanical output occurring during spontaneous respiratory drive, *i.e.* the inspiratory flow or airway depression that the ventilator has to detect in order to synchronise the ventilatory assistance to the patient's inspiratory effort, may be less easy to detect during sleep. Recording the patients during sleep was refrained from, although NPPV is generally performed during sleep, since NPPV is initially started and adapted during wakefulness, before being tested during sleep. In addition, typical patient profiles were used, but, in clinical practice, the presence of several factors favouring nocturnal hypoventilation is a common situation, such as the association of obesity and upper airway obstruction in patients with Duchenne muscular dystrophy. It was not possible to integrate such mixed pathologies in the present bench model. It was also not possible to include dynamic modifications, such as upper airway obstruction and decrease in respiratory drive during sleep. If there is confidence that the ventilators that were unable to detect the simulated respiratory efforts would also be unable to detect respiratory efforts under real-life conditions, it cannot be ascertained that the ventilators considered appropriate by the bench study were effectively appropriate under real-life conditions. Therefore, the present study only permits preselection of ventilatory devices which can be reasonably tested in a paediatric patient, and cannot exclude a clinical evaluation before considering that a ventilator is really appropriate for a child.

Nevertheless, a systematic comparison of bench data with *in vivo* data is lacking. However, for most typical situations, the *in vitro* results are in agreement with *in vivo* patient tracings. Indeed, the lack of detection of the patient's inspiratory and expiratory effort by the majority of the bilevel devices in infants and young children has been previously observed [6]. The insufficient sensitivity of the inspiratory trigger of the Eole 3 XLS has also been observed in young patients with cystic fibrosis [7]. Moreover, the majority of the problems encountered

with the various ventilators during the bench testing have been observed in patients [6].

Practical recommendations

The present results underline the necessity of a systematic bench evaluation of all ventilators proposed for NPPV in children. This evaluation should ideally include assessment of the quality of the inspiratory (pressure and/or flow) trigger and the ability of the ventilator to reach and maintain the preset volume or pressure, as well as to cope with leaks. However, for some patients, such as patients with neuromuscular disease or central apnoea, effort-independent modes are recommended, precluding the evaluation of the inspiratory trigger. This bench evaluation should be followed by a clinical evaluation in the patients for whom the ventilator has shown good or acceptable performances, as defined by specific criteria, *e.g.* those proposed in the present study.

The choice of a ventilator for a specific patient depends upon the patient's characteristics (underlying disease, age and weight), the ventilatory mode to be used and the performance of the ventilator. Other ventilator characteristics, not evaluated in the present study, such as the accuracy of the alarms and the possibility of humidification or additional oxygen therapy, should also be taken into account. Finally, ergonomics, such as transportability and internal battery, are important in clinical use. However, ultimate efficacy must be checked in each individual case by daytime performance and comfort, associated with overnight control.

Conclusion

The present bench study, which, for the first time, evaluated 17 home ventilators for the six most common paediatric profiles, shows that the performance of the ventilators varied according to not only ventilator characteristics (type of circuit and trigger) but, most importantly, also patient profile, including age and weight, as well as underlying disease. Even if different modes and different ventilators may be used in a specific patient, a systematic bench evaluation, coupled to a clinical *in vivo* evaluation, is recommended for all ventilators proposed for home noninvasive positive-pressure ventilation in children.

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