Perinatology
pISSN 2508-4887 • eISSN 2508-4895

Original article
Perinatology Vol. 30, No. 2, June, 2019
https://doi.org/10.14734/PN.2019.30.2.83

Feasibility and Functional Evaluation of Noninvasive Ventilation Capable Equipment from the Delivery Room to Neonatal Intensive Care Unit: A Bench Study

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Objective: The use of noninvasive ventilation (NIV) for newborns requiring respiratory support in delivery room (DR) is recommended. However, the details related to such use are not well established. A bench investigation on the performance of available NIV equipment was conducted.

Methods: Two T-piece resuscitators (TPRs) and three ventilators were tested with a Neonatal Lung Simulator which is capable of recording the pressure, flow, and volume. We measured the pressurization and delivered volume (DV) of nasal continuous positive airway pressure (nCPAP), bubble CPAP (bCPAP)/nasal high-frequency ventilation (nHFV), and synchronized nasal intermittent positive pressure ventilation (SNIPPV) in apneic and breathing models. Temperature and absolute humidity (AH) at the Y-piece were checked for 10 minutes in each setting while the Y-piece on an open bassinet or in a preheated incubator.

Results: The pressurization was well achieved with every combination except for TPRs on nCPAP. DV was well provided using bCPAP/nHFV and SNIPPV in the breathing model. With bCPAP, DV decreased significantly in apneic model. On the bassinet, temperature and AH dropped to ambient temperature and approximately 25 mgH_2O/L within 4 minutes, respectively. In the incubator, temperature and AH on all pre-humidified machines were maintained above 34°C and 30 mgH_2O/L for 5 minutes, respectively. Those without pre-humidification were below 30°C and less than 20 mgH_2O/L, respectively.

Conclusion: Other combination of device/equipment than TPR tested seemed more feasible for nCPAP. The use of equipment with backup ventilation and heated-humidified gas in preheated incubators would be more appropriate NIV for premature infants in DR and during transport.

Key Words: Continuous positive airway pressure, Equipment design, Humidity, Newborn, Transportation

Received: 25 January 2019
Revised: 9 April 2019
Accepted: 30 April 2019

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Introduction

For spontaneously breathing preterm infants requiring respiratory support, initial use of noninvasive ventilation (NIV) rather than routine intubation in the delivery room (DR) has become increasingly recommended to decrease the rate of intubation, the need for surfactant replacement therapy, and the duration of mechanical ventilation with the potential benefit of reduction of mortality.[1,2] Nasal continuous positive airway pressure (nCPAP) is the most commonly used form of NIV.[3] Early initiation of nCPAP after birth regardless of respiratory status in the preterm infant resulted in the reduction of the incidence of bronchopulmonary dysplasia (BPD) without adverse effects[4-6] in spite of the reports of a higher incidence of pneumothorax in multicenter studies.[7] The use of NIV is thought to result in less alveolar injury compared with mechanical ventilation via an endotracheal tube. Administration of surfactant using the Intubation–Surfactant–Extubation procedure requires endotracheal intubation. Thus, less invasive approaches without endotracheal

intubation, such as the technique of minimally invasive surfactant therapy in spontaneous breathing preterm infants with nCPAP, is being applied more frequently based on the premise that avoidance of any positive pressure ventilation may be beneficial.[8–11]

Most recent neonatal resuscitation guidelines recommend techniques to minimize heat loss in the DR. The use of warmed humidified resuscitation gases is the standard of care for preterm infants.[12–14] Moreover, delivery of cold, dry gases may lead to inspissated secretions and airway obstruction, metaplastic changes of the nasal epithelium, and nasal mucosal injury.[15] Even short periods of exposure to inadequate humidification can lead to changes in lung function, particularly in preterm neonates.[16,17] Therefore, it is crucial to deliver heated humidified gases during neonatal resuscitation and transport.[18,19]

Various methods of NIV are available including bubble CPAP (bCPAP), synchronized noninvasive intermittent positive pressure ventilation (SNIPPV) and nasal high-frequency ventilation (nHFV). There are also possible variations of use including differences in pressure and interface devices. In general, manufacturers do not guarantee performance when combining devices not listed in their manual. There are currently no evidence-based recommendations guiding neonatal use of NIV by suggesting the optimal choice of modality or settings. Information on what types of NIV equipment and devices can be used from the DR to the neonatal intensive care unit (NICU) is not yet fully shared. As a result, most NICUs formulate their individualized practices, which rely on personal experiences and preferences.

We assessed the operational performance and the humidification of the several combinations of NIV equipment and interface devices available in the DR and during transport to the NICU on the bench. We also aimed to evaluate the feasibility and practical limitations of using the NIV equipment/devices during resuscitation and transport.

Methods

All measurements were performed at atmospheric pressure, constant room temperature (mean room temperature, 23±1.5°C) between September and October 2017. Before each measurement, the incubator (Incu i®, Atom Medical Corporation, Tokyo, Japan) was warmed to 34°C with a relative humidity (RH) of 60% to provide an approximate representation of the temperature and humidity within the normal neonatal upper airway.[20]

1. Equipment and interface devices

We evaluated the two T-piece resuscitators (TPRs) and three types of NIV equipment available in the NICU: the NeoPuff™ T-piece resuscitator (Fischer & Paykel Healthcare Ltd., Auckland, New Zealand), the NeoPIP™ resuscitation unit (NeoForce Group Inc., Redwood City, CA, USA), the F&P bubble CPAP system (Fischer & Paykel Healthcare Ltd.), the medinCNO® (Medin Medical Innovations Gmbh, Munchen, Deutschland), and the Sophie® neonatal ventilator (Fritz Stephan Gmbh Medizintechnik, Gackenbach, Deutschland). The general characteristics of the equipment and interfaces tested

Table 1. General Characteristics of Equipment/Devices Combinations

Types	Equipment	Controlled pressure	Graphic monitoring	Attached humidifier	Electricity requirements	Interface(s) tested
T-piece resuscitators	NeoPuff™*	Yes	No	No	No	A
	NeoPIP™†	Yes	No	No	No	A
Bubble CPAP	F&P Bubble CPAP*	Yes	No	Yes	No	B and C
Flow-driven positive pressure equipment	medinCNO®‡	No	Yes	Yes	Internal/External	D
Mechanical ventilator	Sophie®§	Yes	Yes	Yes	Internal/External	A and B

Abbreviations: A, Easyflow nCPAP® nasal cannula (Fritz Stephan Gmbh Medizintechnik, Gackenbach, Deutschland); B, Miniflow® generator and prongs (Medin Medical Innovations Gmbh, Munchen, Deutschland); C, FlexiTrunk™ midline interface and nasal cannula (Fisher & Paykel Healthcare Ltd., Auckland, New Zealand); D, Medijet® generator and prongs (Medin Medical Innovations Gmbh).
*Fisher & Paykel Healthcare Ltd., Auckland, New Zealand.
†NeoForce Group Inc., Redwood City, CA, USA.
‡Medin Medical Innovations Gmbh, Munchen, Deutschland.
§Fritz Stephan Gmbh Medizintechnik, Gackenbach, Deutschland.

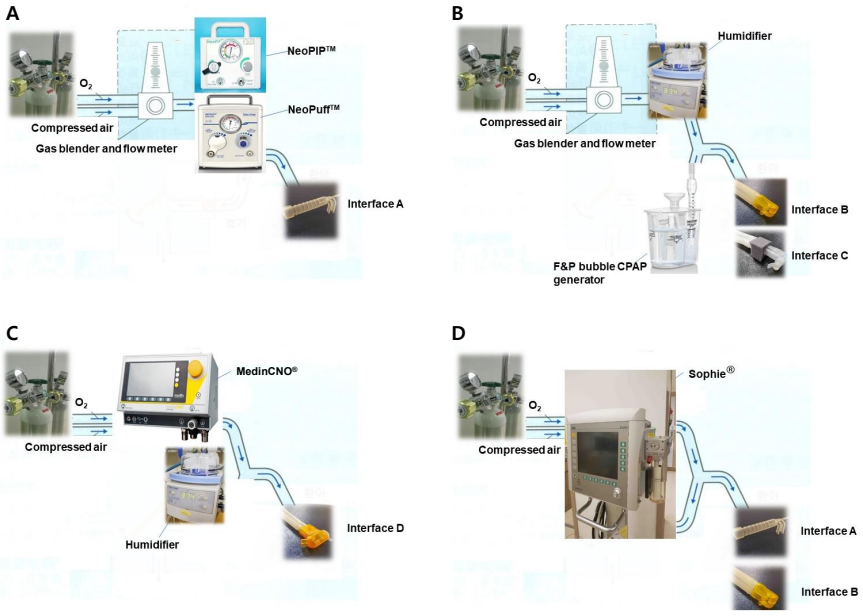

Fig. 1. Schematic representation of the experimental equipment and circuits/interface(s). (A) Two T-piece resuscitators (NeoPuff™ [Fisher & Paykel Healthcare Ltd., Auckland, New Zealand] and NeoPIPTM [NeoForce Group Inc., Redwood City, CA, USA]) were connected to interface A via the non-humidified circuits. (B) The bubble CPAP (F&P bubble CPAP system [Fisher & Paykel Healthcare Ltd.]) was connected to interface B and C via a humidifier. (C) The flow-driven positive pressure equipment (medinCNO® [Medin Medical Innovations Gmbh, Munchen, Deutschland]) was connected to interface D. (D) The mechanical ventilator (Sophie® [Fritz Stephan Gmbh Medizintechnik, Gackenbach, Deutschland]) was connected to interface A and B. Interface A, Easyflow nCPAP® nasal cannula (Fritz Stephan Gmbh Medizintechnik); Interface B, Miniflow® generator and prong (Medin Medical Innovations Gmbh); Interface C, FlexiTrunkTM midline interface and nasal cannula (Fisher & Paykel Healthcare Ltd.); Interface D, Medijet® generator and prongs (Medin Medical Innovations Gmbh); CPAP, continuous positive airway pressure.

are shown in Table 1. Each piece of equipment was connected to a neonatal active lung model (Gina®, Dr. Schaller Medizintechnik, Dresden, Deutschland) via nasal interfaces (Fig. 1).

2. Simulation and measurement

The neonatal active lung model was used to simulate spontaneous breathing and perform dynamic measurements. We set the simulated compliance, resistance, and respiratory rate to represent a 1 kg preterm neonate with low compliance and weak respiratory drive: compliance, 0.4 mL/cmH_2O; respiratory muscle pressure, 3 hectoPascal (hPa, 1 hPa=1.0197 cmH_2O); respiratory rate, 60 breaths/min; inspiration time, 0.3 seconds; inspiratory time constant, 30 msec; expiratory time constant, 30 msec by reviewing previous neonatal bench studies.[21-24] The airway pressures and the delivered volume (DV) with or without simulated self-breathing were measured for 20 seconds, using the lung simulator attached to the Y-piece. Each test was performed after the external electrical power supply for the equipment was disconnected, and the equipment operated with internal batteries.

3. Experimental setting

Three different modes of NIV were evaluated: nCPAP (two TPRs, the medinCNO®, and the Sophie®), bCPAP/nHFV (the F&P bubble CPAP system, the medinCNO®, and the Sophie®) and SNIPPV (the medinCNO® and the Sophie®). Set pressures and gas flows were chosen to encompass the general range of levels used in normal neonatal practice.

1) nCPAP mode

Two TPRs were tested at the pressure reading of 6 cmH_2O by each TPR with gas flow at 7 liters per minute (lpm). In the

medinCNO® which is flow-driven equipment, we set the gas flow to 7 lpm. For the Sophie®, which supplies demand flow, we set the positive-end-expiratory-pressure (PEEP) to 5 cmH_2O.

2) bCPAP/nHFV mode

In the F&P bubble CPAP system, the gas flow was set to 7 lpm with the water level of 7 cmH_2O. The medinCNO® was tested at 4 lpm of inspiratory flow and basal flow of 7 lpm, with a step (amplitude) of 10 and a frequency of 8 Hz. The Sophie® was set to a mean airway pressure (MAP) of 5 cmH_2O, frequency of 8 Hz, and amplitude of 10.

3) SNIPPV mode

The medinCNO® was set with an inspiratory flow of 4 lpm, a basal flow of 7 lpm, and backup ventilation for apneic episodes. Backup ventilation was set at a respiratory rate of 60 with the same flow rate. The Sophie® was set to a peak inspiratory pressure (PIP) of 15 cmH_2O and a PEEP of 5 cmH_2O. Backup breathing in the absence of spontaneous breathing was set to a respiratory rate of 60 at the same pressure setting. The maximum, minimum, and mean pressures were measured. Means and standard deviations were calculated to ensure that the set values were maintained.

4. Temperature and absolute humidity (AH) measurement

The temperature and humidity were checked at the proximal sensor on the Y-piece using the PMH8000 (Pacific Medico® Co. Ltd., Tokyo, Japan). Since the TPRs have no internal humidifier, a 10 lpm of cold, dry oxygen was connected to the inlet opening and measurement was performed at the proximal sensor inside the incubator. For the F&P bubble CPAP system, an MR290™ chamber on the MR850™ humidifier (Fischer & Paykel Healthcare Ltd.) and breathing circuit (Fisher & Paykel Healthcare Ltd., Auckland, New Zealand) were connected nasal interface. For the medinCNO®, a humidification chamber of the Medin circuit was attached to the MR850™ humidifier. The Sophie®, which has its internal humidifier and circuit, was measured with a set proximal temperature of 39°C and humidity "++". After 20 minutes of heating in the invasive ventilation mode of the MR850TM, the humidifier was turned off, and the changes in temperature and humidity were recorded every 1 minute over a total period of 10 minutes at the proximal sensor. This 10 minutes recording period was performed with the proximal sensor and circuit placed on the open bassinet and repeated later with the proximal sensor and circuit inside the prewarmed incubator or vice-versa. In all settings, the humidifier was set to a target temperature of 37°C (invasive ventilation mode) and full saturation, as recommended by the manufacturers. The humidity compensation (HC) was set to 0.0 of MR850™, and in the nHFV mode of the medinCNO®, measurements were also taken at HC+3.0 of MR850™.

Following each temperature/humidity recording period, the thermohygrometer was removed, and the circuit and probe were removed from the incubator, dried, then returned to the incubator and allowed to re-acclimatize to the incubator conditions. After completion of the measurements, AH values in mgH_2O/L were calculated with the temperature and RH using the Vaisala humidity calculator (http://go.vaisala.com/humiditycalculator/5.0/).

5. Statistic and data analysis

A statistical description was performed using MedCalc version 18 (MedCalc Software, Ostend, Belgium). All measured and calculated data are presented as means and standard deviations.

Results

1. nCPAP mode

The set CPAP pressure was better maintained in the medin CNO® and the Sophie® than with the Neopuff™ and NeoPIP™. The DV was similar in all equipment (Table 2). There was no difference in measured pressure with or without self-respiration, except for in the NeoPuff™. In the NeoPuff™, measured pressure was 5.08±0.03 cmH_2O in apneic conditions and 4.61±0.24 cmH_2O in breathing conditions at the level of a target PEEP of 6 cmH_2O.

2. bCPAP/nHFV mode

In the bCPAP or nHFV modes, unlike in nCPAP, the DVs were produced by the oscillatory pressure even during the non-breathing period (Table 3). In the medinCNO® and the Sophie®, the DVs were constant regardless of spontaneous

Table 2. Measured Pressure and Delivered Volume in Nasal Continuous Positive Airway Pressure Mode

Equipment	Interface (s)	O_2 flow (L/min)	Pressure (cmH_2O)	Simulated self-respiration	Measured Pmean±SD (cmH_2O)	Delivered volume±SD (mL)
NeoPuff™*	A	7	6	No	5.08±0.03	
				Yes	4.61±0.24	0.94±0.13
NeoPIP™†	A	7	6	No	4.34±0.03	
				Yes	4.32±0.21	0.85±0.12
medinCNO®‡	D	7		No	5.55±0.09	
				Yes	5.51±0.14	0.79±0.13
Sophie®§	A		5	No	5.31±0.10	
				Yes	5.31±0.14	1.05±0.14
	B		5	No	5.29±0.15	
				Yes	5.29±0.18	1.06±0.07

Abbreviations: SD, standard deviation; Pmean, mean pressure; A, Easyflow nCPAP® nasal cannula (Fritz Stephan Gmbh Medizintechnik, Gackenbach, Deutschland); B, Miniflow® generator and prongs (Medin Medical Innovations Gmbh, Munchen, Deutschland); D, Medijet® generator and prongs (Medin Medical Innovations Gmbh).
*Fisher & Paykel Healthcare Ltd., Auckland, New Zealand.
†NeoForce Group Inc, Redwood City, CA, USA.
‡Medin Medical Innovations Gmbh, Munchen, Deutschland.
§Fritz Stephan Gmbh Medizintechnik, Gackenbach, Deutschland.

Table 3. Measured Pressure and Delivered Volume in Bubble Continuous Positive Airway Pressure/Nasal High Frequency Ventilation Mode

Equipment	Interface	O_2 flow (L/min)	Pressure (cmH_2O)	Simulated self-respiration	Measured Pmax (cmH_2O)	Measured Pmin (cmH_2O)	Measured Pmean±SD (cmH_2O)	Delivered volume±SD (mL)
F&P bubble CPAP*	B	7	7	No	9.00	5.32	7.10±0.78	0.36±0.05
				Yes	8.77	5.11	7.13±0.69	0.69±0.18
	C	7	7	No	8.57	5.81	7.21±0.69	0.37±0.04
				Yes	8.66	5.52	7.21±0.66	0.74±0.24
medinCNO®†	D	7+4		No	8.87	1.52	5.64±2.64	0.97±0.11
				Yes	9.11	1.28	5.64±2.64	0.94±0.19
Sophie®‡	A	Amplitude 10	5	No	9.25	1.84	4.66±2.71	0.90±0.05
				Yes	9.32	1.56	4.68±2.70	0.98±0.12
	B	Amplitude 10	5	No	10.2	0.55	4.89±3.22	1.06±0.17
				Yes	10.7	0.47	4.94±3.22	1.08±0.23

Abbreviations: Pmax, maximum pressure; Pmin, minimum pressure; Pmean, mean pressure; SD, standard deviations; B, Miniflow® generator and prongs (Medin Medical Innovations Gmbh, Munchen, Deutschland); C, FlexiTrunk™ midline interface and nasal cannula (Fisher & Paykel Healthcare Ltd., Auckland, New Zealand); D, Medijet® generator and prongs (Medin Medical Innovations Gmbh); A, Easyflow nCPAP® nasal cannula (Fritz Stephan Gmbh Medizintechnik, Gackenbach, Deutschland).
*Fisher & Paykel Healthcare Ltd., Auckland, New Zealand.
†Medin Medical Innovations Gmbh, Munchen, Deutschland.
‡Fritz Stephan Gmbh Medizintechnik, Gackenbach, Deutschland.

breathing, contrary to the bCPAP mode in which the DV was variable (Fig. 2). In the bCPAP, the mean pressure was well established at a PEEP of 7 cmH_2O with a flow of 7 lpm which is the common setting for bCPAP. In the medinCNO®, the nHFV mode produced more DV than with nCPAP mode.

3. SNIPPV

The SNIPPV mode has a sufficient supply of tidal volume compared to the other two modes. There was no difference in DV according to device combination. The SNIPPV produced the highest DV at the same pressure. Volume delivery was better achieved during self-respiration (Table 4).

4. Temperature and humidity changes

When the ventilator circuit and proximal sensor were placed on the open bassinet, the temperature acutely dropped from

approximately 38°C to 30°C, and the humidity dropped to approximately 25 mgH_2O/L within approximately 4 min in every combination of preheated humidified device/equipment.

However, when the circuit and sensor were placed inside the preheated incubator, the temperature and humidity were maintained for at least 5 minutes and gradually dropped (Fig. 3). Mean temperature and AH remained higher during nCPAP with the Sophie®. With TPR, which was not capable of supplying heated-humidified air, the temperature remained below 30°C. When the Sophie® was not preheated-humidified, the temperature remained around 30°C even when the proximal sensor was kept inside the incubator.

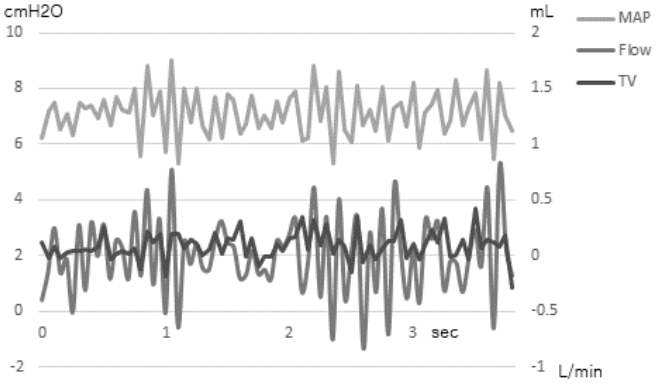

Fig. 2. The waveforms of mean airway pressure (gray), airflow (dark gray) and delivered tidal volume (black) recorded by a lung simulator during non-breathing in the F&P bubble CPAP system (Fisher & Paykel Healthcare Ltd., Auckland, New Zealand). The pressure was set at 7 cm, and the flow was set at 7 liter/min. The pressure waveform of bCPAP showed intermittent increased pressure which was thought to be aroused by the water movement in the exhalation limb of the circuit. The waveform exhibited approximately 8 Hz frequency waves. MAP, mean airway pressure; TV, tidal volume; bCPAP, bubble continuous positive airway pressure.

Discussion

The most critical action in the resuscitation of a depressed newborn in the DR is to establish effective ventilation.[2] NIV is considered the optimal method of providing respiratory assistance to breathing preterm babies.[25] Although nCPAP is widely used in neonates as it is less injurious to the lung, the protocol for its use during transport has not yet been established. This study evaluated several combinations of NIV machines and devices regarding pressurization, volume delivery, and the changes in the temperature and humidity in simulated transport conditions. We found that there were mode-specific differences in the performance characteristics of tested combinations of equipment/devices. For the nCPAP mode, the medinCNO® and the Sophie® showed better pressurization than the two TPRs. Volume delivery was better achieved by the SNIPPV mode than the nCPAP or nHFV. When the ventilator circuit was placed inside the preheated incubator, the temperature and AH on preheated-humidified settings maintained for up to 5 minutes, then gradually dropped.

We found the TPRs did not reach the predetermined target pressure and could not provide tidal volume in the apneic situation. The measured delivered CPAP level in the NeoPuff™ was lower in the simulated breathing condition compared to the apneic condition. This phenomenon may be due to that the TPR did not have the ability to compensate the negative

Table 4. Measured Pressure and Delivered Volume in Synchronized Nasal Intermittent Positive Pressure Ventilation Mode

Equipment	Interface	O_2 flow (L/min)	Pressure (cmH_2O)	Simulated self-respiration	Measured Pmax (cmH_2O)	Measured Pmin (cmH_2O)	Measured Pmean±SD (cmH_2O)	Delivered volume±SD (mL)
medinCNO®*	D	7+4		No	11.6	5.02	6.43±1.88	1.74±0.75
				Yes	11.8	5.14	6.83±2.10	2.28±0.42
Sophie®†	A		15+5	No	14.6	4.49	7.75±4.07	4.28±0.05
				Yes	15.2	4.46	8.69±4.25	4.43±0.37
	B		15+5	No	14.6	4.51	7.57±3.68	4.11±0.07
				Yes	16.1	4.59	8.28±3.88	4.33±0.34

Abbreviations: Pmax, maximum pressure; Pmin, minimum pressure; Pmean, mean pressure; SD, standard deviations; D, Medijet® generator and prongs (Medin Medical Innovations Gmbh, Munchen, Deutschland); A, Easyflow nCPAP® nasal cannula (Fritz Stephan Gmbh Medizintechnik, Gackenbach, Deutschland); B, Miniflow® generator and prongs (Medin Medical Innovations Gmbh).
*Medin Medical Innovations Gmbh, Munchen, Deutschland.
†Fritz Stephan Gmbh Medizintechnik, Gackenbach, Deutschland.

respiratory drive on self-respiration. Also, even though the circuit and sensor were placed inside the preheated incubator, the TPR without the extra/external humidifier could not supply adequately heated-humidified air. Directly connecting humidified oxygen to the inlet of the TPR is not recommended because of the accumulation of water droplets in the TPR which can possibly lead to infection and malfunction of the devices. A study of preterm infants born less than 33 weeks of gestation showed more hypothermia on admission if they received positive pressure ventilation in the DR with unheated gas and if they received respiratory support during transport to the NICU.[26] Another study reported that there is an increased incidence of pneumothorax and severity of BPD in infants <1,500 g exposed to cold, dry gas.[17] During stabilization and transport while using a TPR, gas conditioning by the external humidification chamber and the heated patient circuit is available and beneficial.[27] However, another bench study found the temperature at the T-piece, distal probe and humidifier chamber did not reach the target values described in the operator's manual.[18] The clinical application of TPR would be limited, due to the limited time available and a more laborious setup of extra/external humidifier and circuit. Clinicians need to be aware of differences in the efficacy of heating and humidification when choosing modes of NIV.

We measured the temperature and humidity via the PMH8000 widely used in Japanese NICUs. The PMH8000 has an integral temperature and humidity probe equipped with monitoring and control of temperature and RH. According to the manu-

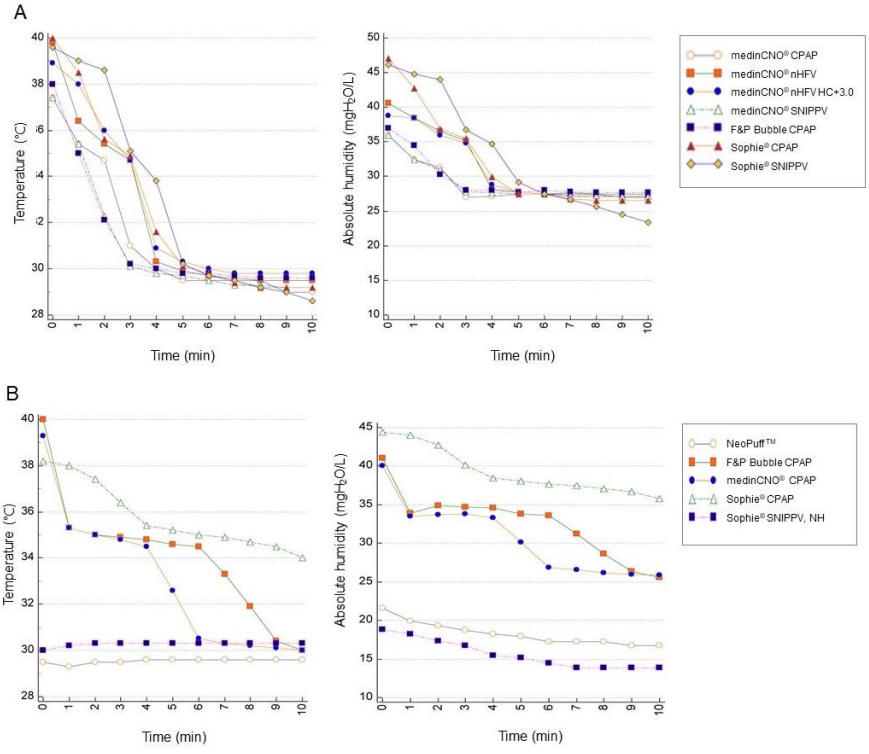

Fig. 3. Time course of changes in temperature and absolute humidity. (A) On the open bassinet, the temperature dropped below 30℃, and the humidity dropped to about 25 mgH_2O/L in about 4 minutes in every mode of preheated equipment. (B) In the incubator, the temperature and absolute humidity were maintained for about 5 minutes and gradually dropped. In the NeoPuffTM (Fisher & Paykel Healthcare Ltd., Auckland, New Zealand) and non-heated/non-humidified Sophie® (Fritz Stephan Gmbh Medizintechnik, Gackenbach, Deutschland), the temperature remained around 30℃ and the humidity also decreased, even though the proximal sensor was kept inside the incubator. CPAP, continuous positive airway pressure; nHFV, nasal high-frequency ventilation; HC, humidity compensation; SNIPPV, synchronized nasal intermittent positive pressure ventilation; NH, non-heated & non-humidified.

facturer, this device is reported to be accurate to within ±0.5°C temperature and ±1.0% RH. The probe was positioned within the Y connector, such that the sensor of the probe was held in the center of the gas flow. The amount of water vapor in a gas mixture can be expressed as AH or RH at a certain temperature. AH is the total water present in the gas (mgH_2O/L), and RH is the amount of water present as the percentage of maximum carrying capacity at a given temperature. The human airway must provide gas at core temperature and 100% RH at the alveolar surface to optimize gas exchange and protect lung tissue.[28] At body temperature (37°C), the air has an AH of 44 mg/L if 100% saturated (100% RH), whereas at 30°C, the air has an AH of 30 mg/L.[19] The International Organization for Standardization specifies that for all patients with an artificial airway, humidifiers must deliver an AH of ≥33 mgH_2O/L. Because NIV is usually delivered through a nasal or oro-nasal interface, the inspired gas is conditioned through the upper airway. For spontaneously breathing non-intubated premature infants, it is unclear what the target temperature and RH should be where the nasal mucosa and upper respiratory tract are exposed to the delivered gas. Hospital gas delivery systems supply only cold and dry gas, with a temperature of approximately 23°C and an RH of less than 5%.[29] During neonatal respiratory support with a heated humidifier, condensation following decreases in temperature within the inspiratory circuit would become serious problems by reducing AH and the complication induced by the water droplets. The delivery of optimally humidified gas to the lungs would be limited because of the reduced AH in the gas.[30] When the water droplets get in the airway of the infants, it would cause accidental lavage, peripheral airway obstruction, reduced mucus transport, and surfactant dilution in those airways.[28] The humidity in a ventilator circuit is easily affected by the temperature around the circuit. Consequently, a temperature drop induces a decrease in AH in the ventilator circuit.[31] Therefore, even in a preheated circuit, it is necessary to keep the circuit in the incubator to maintain the circuit warmth and humidity during transport.

In the present study, we simulated a single model with low compliance and weak respiratory drive. A pneumatic input of the lung model, called Gina, was connected pneumatically to the NIV equipment via the nasal interface and Y piece. Gina enables the simulation of different breathing mechanism parameters such as different ventilation tubes and different airway resistances and features internal compliance which is adjustable using the software. Additionally, Gina enables the simulation of the patient's spontaneous breathing. The volume flows, volumes and pressures are measured and represented numerically as well as graphically.[32] The point of using simulation is to highlight the basic physics of the patient-ventilator system under ideal conditions to help understand the clinical implications of the NIV equipment/devices. During transport to the NICU, portable compressed air and oxygen are required. In our preliminary test, the pressures generated by cylinder oxygen and air were not different from those of the wall oxygen/air supplies. Additionally, the amount of gas consumption was well correlated with the expected amount of consumption predicted by the formula described in the previous study (data not shown).[33] The F_IO_2 was not measured because a calibrated oxygen blender and calibrated instrument were used.

bCPAP transmits small-amplitude, high-frequency pressure around the MAP and may be more beneficial than nCPAP to aid in lung recruitment and to improve gas exchange.[34] Infants on bCPAP have been reported to have chest wall vibrations similar to those with HFV.[35] Our study also showed that the bCPAP or nHFV modes produce proper DV even in apnea by the pressure difference due to vibration. However, unlike nHFV through a mechanical ventilator, bCPAP systems cannot provide variable flow at the nares.[22] Interestingly, the pressure waveform of bCPAP showed intermittent increased pressure which was thought to be aroused by the water movement in the exhalation limb of the circuit (Fig. 2). These pressure rise would produce deep inspiration/expiration or sigh. Further research would be required on this phenomenon. The MAP and oscillatory effects may be different depending on the flow, device, circuits, and patient interfaces used in bCPAP mode. The MAP would increase with increasing flow even though the depth of the water level remained the same. Flow can increase resistance to spontaneous breathing or fail to meet inspiratory demands.[22,36] Manufacturer's guideline describes the mean pressures is 7.6 cmH_2O on a flow of 7 lpm and CPAP probe at 7 cmH_2O when the F&P bubble CPAP generator is used with F&P infant interface with no leak.[37] In our results, the measured delivered pressures reached the manufacturer's target level

in both testing combination of different interfaces. However, DV decreased significantly in the apneic model, unlike the nHFV and SNIPPV modes. We guess bCPAP would be a useful equipment/device for transporting premature infants with spontaneous breathing from DR to NICU and using continuously in NICU. However, there was one report showing that bCPAP was associated with greater breathing asynchrony and higher work of breathing than variable flow nCPAP devices in premature infants.[38] On the other hand, using graphic monitor in NIV with mechanical ventilator was shown to be effective in reducing a significant leak, acquiring better adjustments, and achieving a lower rate of excessive DV by enabling feedback on delivered pressures and volumes.[39] Additionally, NIV with mechanical ventilator can be quickly switched to invasive ventilation when escalation of respiratory support is required after NICU admission.

This study evaluated the equipment and devices at settings commonly used in the neonatal unit. However, the limitation is that the study was performed on a simulating model. Our study did not have a leak in the system. Whatever the type of interface used, variable leaks will always be present in the clinical application, because of imperfect fitting, mouth opening, and infants' movements. These limitations should raise caution regarding the translation of the exact pressurization and DV results into neonates, whose lung mechanics may also differ. Another limitation was that the F_IO_2 was not tested although humidity of the delivered gases during NIV may be influenced by F_IO_2.[40] Further studies should be performed to assess the ergonomics of these equipment/devices in an actual clinical situation. We did not intend to make comparisons between devices within a similar category. We were not able to guide the setting of inspiratory pressure on the ventilator. Our purpose is to evaluate the performances and general characteristics of each NIV ventilator in simulated transport situation before clinical uses. Clinicians should be aware of the differences found among these ventilators when choosing these important devices for transport.

In conclusion, each combination of equipment and devices was capable of supplying tolerable pressure and volume, except TPRs. TPRs without a humidifier or mechanical ventilators with a non-preheated humidifier could not deliver the proper temperature and humidity during resuscitation and transport. Portable cylinders, preheated humidifier, and an incubator are recommended for continued respiratory support with NIV when transporting an infant from the DR to the NICU. Equipment with backup ventilation and variable flow capabilities should be used in preterm infants with an unstable respiratory drive.

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