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Performance of Different Active Humidification Systems in High-Flow Oxygen Therapy

Gustavo A Plotnikow, Darío Villalba, Emiliano Gogniat, Corina Quiroga, Eliana Pérez Calvo, and José Luis Scapellato

BACKGROUND: We sought to evaluate the performance in terms of absolute humidity (AH), relative humidity (RH), and temperature of different heated humidifiers (HH) and circuits that are commonly used to deliver high-flow oxygen therapy in conventional ranges (30–60 L/min) and unconventional ranges (70–100 L/min). METHODS: In this prospective, observational study, an electronic thermohygrometer was used to obtain the required measurements. A mechanical ventilator was used as a source for high-flow nasal cannula oxygen therapy. For active humidification, the following equipment was used: a HH with standard disposable water trap circuit, 3 servo-controlled HH, and 7 circuits with a heated wire. Data on environmental conditions (ie, temperature, RH, AH) were collected from the laboratory during each measurement; the temperature, RH, and AH resulting from the application of 8 flows (30–100 L/min) were also recorded. Variables were compared with analysis of variance for repeated measurements with Tukey post hoc tests. A value of $P < .05$ was assumed to be significant. RESULTS: During the study, a statistically significant difference was found in the average AH for each flow for the different devices ($P < .005$). The highest AH values were recorded with the Fisher & Paykel MR850 and the Medtronic-DAR circuit (AH = 40.8 mg/L with flow of 50 L/min, $P < .005$), and the lowest AH values were recorded with the Flexicare FL9000 HH and the Flexicare circuit (AH = 11.4 mg/L with 100 L/min flow, $P < .005$). For flows > 50 L/min, the best performance for all flows in terms of AH was found with the Fisher & Paykel MR850 HH, regardless of the circuit used. CONCLUSIONS: During oxygen therapy with very high gas flows, HH devices behave differently and in many cases are inefficient in delivering adequate humidification, even at conventional flows. Caution is therefore recommended when selecting the device and flow settings for the implementation of high-flow nasal cannula oxygen therapy. *Key words: high-flow oxygen therapy; active humidification; oxygen; intensive care unit.* [Respir Care 0;0(0):1–●. © 0 Daedalus Enterprises]

Introduction

High-flow nasal cannula (HFNC) oxygen therapy allows humidified oxygen to be delivered at high flows (up to 60 L/min) by controlling F_{IO_2}.[1,2] The use of HFNC in ICUs has increased due to the benefit it has shown in the treatment of certain pathologies. There is currently sufficient evidence to support the implementation of HFNC in

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patients with acute hypoxemic respiratory failure[3] as well as for the prevention of re-intubation of low-risk patients.[4]

Although the mechanisms by which this therapy is effective are still under debate, we know that the use of high flows of up to 60 L/min washes out carbon dioxide[5] from the upper airway, delivers some level of positive pressure,[6,7] and consequently has some effect on end-expiratory lung volume.[8,9] In 2015, a study reported that flows of up to 100 L/min result in an increase in pharyngeal airway pressure of 1 cm H_2O for every 10 L/min flow. Therefore, therapy with very high gas flows (ie, > 60 L/min) could have a higher beneficial effect (ie, as flow increases, breathing frequency decreases).[10] However, flows > 60 L/min could be poorly tolerated by patients, and therefore using very high flows might not be clinically relevant.

Regarding the devices that condition gas for administration through HFNC, few studies have evaluated performance in terms of the temperature and humidity delivered. In these studies, 2 commercial brands of equipment are compared with their respective heater-wire circuits, and only in one of these studies is high gas flow evaluated, with 90 L/min being the maximum flow evaluated.[11,12]

The objective of this study was to evaluate the performance of different brands of heated humidifiers (HH) and circuits, in terms of absolute humidity (AH), relative humidity (RH), and temperature, during the use of HFNC at conventional (ie, 30–60 L/min) and unconventional (ie, 70–100 L/min) flow ranges.

QUICK LOOK

Current knowledge

The use of the heated humidifiers and circuits during high-flow nasal cannula oxygen therapy is recommended to optimize the humidity delivered and to improve patient comfort and compliance.

What this paper contributes to our knowledge

Heated humidifiers and circuits behaved differently during high-flow oxygen therapy, and in many cases they were inefficient in delivering adequate humidification even at conventional flows (< 60 L/min). This can negatively affect patient comfort and treatment tolerance, and it could impair the function of ciliary epithelium and clearance of secretions.

Methods

We performed this prospective observational study in the Sanatorio Anchorena equipment analysis laboratory between June 5 and July 20, 2019. To obtain humidity measurements, an electronic thermohygrometer (605-H1, Testo, West Chester, Pennsylvania) was used (temperature range: 0–50°C, accuracy ± 0.5°C; humidity accuracy up to 95%). A microprocessor-controlled ventilator device (Savina 300, Dräger, Lübeck, Germany) was used to deliver HFNC. For active humidification, the following equipment was tested: a Cloud HH (MARK SRL, La Plata, Argentina) with a standard disposable water trap circuit, 3 servo-controlled HHs (Fisher & Paykel MR850, Auckland, New Zealand; FL9000, Flexicare, Mountain Ash, Wales; AquaVENT, Armstrong, Coleraine, Ireland), and 7 circuits with a heater-wire (RT202, Fisher & Paykel; Evaqua 2, Fisher & Paykel; Medtronic-DAR, Mirandola, Italy; Flexicare; Intersurgical, Wokingham, United Kingdom; AquaVENT; GGM, Changhua, Taiwan). Environmental temperature, RH, and AH were collected from the laboratory during each measurement, and the temperature, RH, and AH resulting from the application of each of the flows were recorded at the distal end of the circuit (Fig. 1).

Measurement Procedure

The Cloud HH was evaluated with the highest device temperature level (ie, level 9) and the servo-controlled HH in noninvasive mode. The 7 heater-wire circuits were randomly combined with each device, and each combination was evaluated with flows of 30, 40, 50, 60, 70, 80, 90, and 100 L/min following a random sequence generated online (https://www.randomization.com). During the study, recordings of 22 flow sequences were performed. Each was composed of 9 sets of temperature, RH, and AH measurements (ie, of the environment and of each of the 8 flows). The protocol for the measurements during the study was is described as follows.

1. Fill the chambers with distilled water with sufficient volume for the entire duration of testing.
2. Turn on the HH in noninvasive mode for servo-controlled HH, or at level 9 for the Cloud HH and attached circuits. Turn the device on (no flow, and the housing filled with distilled water) and allow 5 min for device stabilization.
3. Record the environmental laboratory measurements (temperature, RH and AH) at the end of the initial 5 min of stabilization.
4. Activate the ventilator flow at 20 L/min for 5 min.
5. After 5 min of flow at 20 L/min, set the ventilator the flow for the initial measurement according to the randomization sequence. Allow the device to stabilize for 10 min at each of the programmed flows before taking the measurements.
6. Measurements consisted of a series of 3 recordings over 3 min (1 per minute). In each minute, temperature, RH, and a calculation of the AH corresponding to that measurement were recorded.

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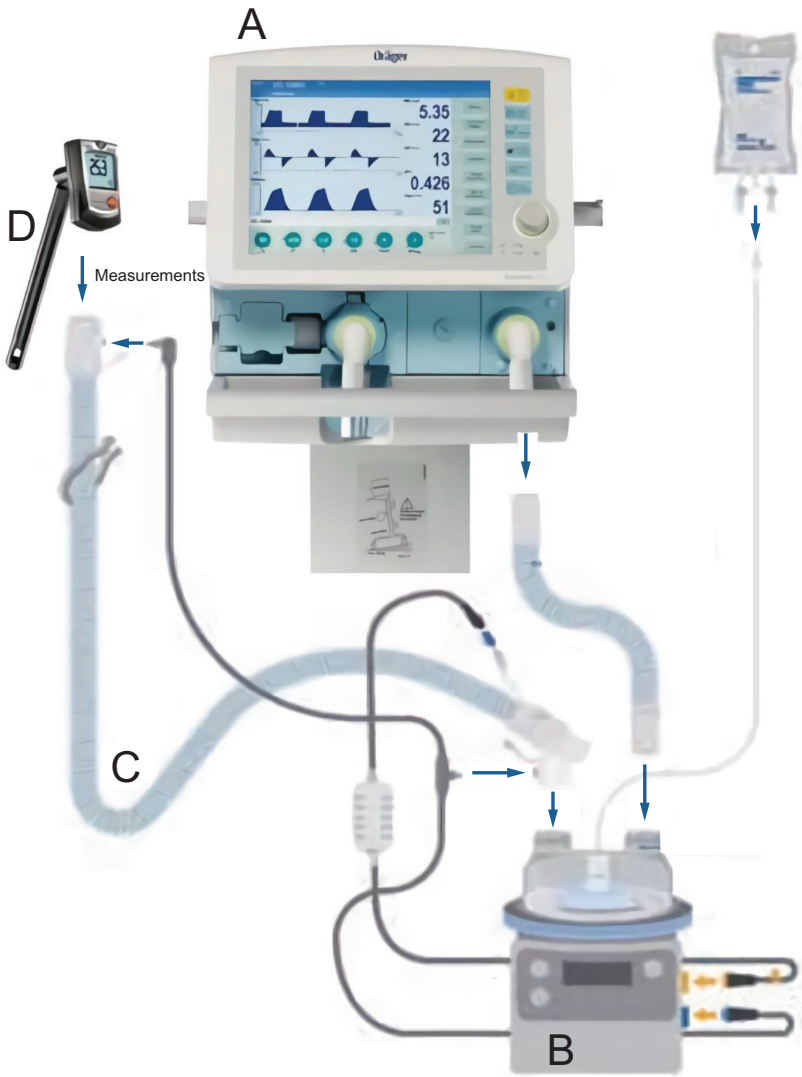

Fig. 1. Assembly and measurement: (A) Mechanical ventilator to generate oxygen therapy at high flows (Savina 300, Drger); (B) servo-controlled heated humidifier; (C) heater-wire circuit; (D) thermohygrometer (Testo 605-H1).

7. Although the system reached its stabilization in 1 min, to avoid the influence of one measurement on the next one, we allowed a period of 3 min between each measurement (ie, zero movement).
8. At the end of the complete measurement sequence, which required 2 h, the presence or absence of condensation in the circuits was noted (ie, yes or no).

Statistical Analysis

Continuous data were expressed as mean ± SD or as median and interquartile range according to their frequency distribution. Normality was assessed by visual inspection and with the Shapiro-Wilk test. Categorical data were expressed as absolute values or percentages. Variables were compared using analysis of variance for repeated measurements. We performed a marginal model analysis. After testing the model with different covariance structures, we selected the best one according to the Akaike information criterion. For multiple comparison, we used the Tukey post hoc test. A value of $P < .05$ was considered significant. For statistical analysis, we used SPSS 25.0 (IBM, Armonk, New York).

Results

The average environmental temperature of the laboratory was 21.6 ± 1.2°C, with an RH of 44.8 ± 3.5% and an AH of 8 ± 2.4 mg/L. During the study, a statistically significant difference was noted in the average AH for each flow between the different combinations of devices and circuits ($P < .001$) (Table 1 and Table 2). T1-2

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Table 1. Temperature, Relative Humidity, and Absolute Humidity for Different Devices and Circuits at Conventional Flows of 30–60 L/min

Cloud Heated Humidifier				Standard Disposable Water Trap Circuit			
Temperature, °C				27.54 ± 0.76			
Relative humidity, %				98.13 ± 0.15			
Absolute humidity, mg/L				26.32 ± 1.25			
Fisher & Paykel MR850 Heated Humidifier							
	Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5	Circuit 6	Circuit 7
Temperature, °C	35.91 ± 1.25	37.33 ± 0.19	36.47 ± 0.86	38.98 ± 1.06	36.66 ± 0.11	34.26 ± 0.46	33.53 ± 0.45
Relative humidity, %	84.78 ± 1.96	87.08 ± 1.22	91.45 ± 3.26	74.61 ± 4.14	85.34 ± 0.9	89.94 ± 1.67	83.72 ± 4.83
Absolute humidity, mg/L	34.96 ± 1.62	38.08 ± 0.53	38.84 ± 1.48	36.11 ± 1.04	36.89 ± 0.82	33.85 ± 1.25	30.17 ± 2.5
Flexicare FL9000 Heated Humidifier							
	Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5	Circuit 6	Circuit 7
Temperature, °C	33.35 ± 1.25	29.13 ± 0.4	33.78 ± 0.14	33.79 ± 0.07	33.35 ± 0.22	32.78 ± 0.22	33.18 ± 0.44
Relative humidity, %	75.42 ± 1.96	68.61 ± 5.4	45.64 ± 2.8	36.44 ± 1.86	63.04 ± 4.15	65.84 ± 5.34	70.76 ± 5.6
Absolute humidity, mg/L	27.14 ± 1.62	19.91 ± 2.19	17.12 ± 1.05	13.66 ± 0.7	22.69 ± 1.44	23.08 ± 1.73	25.33 ± 1.38
AquaVENT Armstrong Heated Humidifier							
	Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5	Circuit 6	Circuit 7
Temperature, °C	33.6 ± 0.11	33.43 ± 0.14	33.21 ± 0.81	34.29 ± 0.17	32.72 ± 0.42	33.23 ± 0.13	33.89 ± 0.51
Relative humidity, %	72.22 ± 10.09	80.46 ± 1.5	81.43 ± 2.03	75.83 ± 1.19	78.28 ± 6.52	70.70 ± 6.68	65.53 ± 3.46
Absolute humidity, mg/L	26.73 ± 3.83	28.98 ± 1.05	29.07 ± 0.69	28.39 ± 0.46	27.35 ± 1.72	25.12 ± 2.38	24.56 ± 1.3

Data are presented as median ± SD. Circuit 1: Fisher & Paykel RT202 heater-wire circuit; Circuit 2: Fisher & Paykel Evaqua 2 heater-wire circuit; Circuit 3: Medtronic-DAR heater-wire circuit; Circuit 4: Flexicare heater-wire circuit; Circuit 5: Intersurgical heater-wire circuit; Circuit 6: AquaVENT heater-wire circuit; Circuit 7: GGM heater-wire circuit.

Table 2. Temperature, Relative Humidity, and Absolute Humidity for Different Devices and Circuits at Unconventional Flows of 70–100 L/min

Cloud Heated Humidifier				Standard Disposable Water Trap Circuit			
Temperature, °C				25.39 ± 0.54			
Relative humidity, %				98.16 ± 0.13			
Absolute humidity, mg/L				23.22 ± 0.7			
Fisher & Paykel MR850 Heated Humidifier							
	Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5	Circuit 6	Circuit 7
Temperature, °C	36.56 ± 0.81	36.18 ± 1	36.97 ± 0.48	36.68 ± 0.82	36.18 ± 1.4	34.53 ± 0.19	34.35 ± 0.48
Relative humidity, %	82.24 ± 0.96	85.38 ± 0.97	85.74 ± 0.93	79.69 ± 1.41	84.65 ± 0.32	87.18 ± 2.75	84.91 ± 2.95
Absolute humidity, mg/L	34.80 ± 1.76	36.02 ± 1.97	37.38 ± 1.23	33.88 ± 1.83	35.61 ± 2.68	33.84 ± 0.95	32.54 ± 1.64
Flexicare FL9000 Heated Humidifier							
	Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5	Circuit 6	Circuit 7
Temperature, °C	33.61 ± 0.24	30.18 ± 0.21	33.91 ± 0.12	33.76 ± 0.09	33.59 ± 0.14	33.08 ± 0.05	33.54 ± 0.23
Relative humidity, %	69.25 ± 2.06	60.81 ± 1.71	43.88 ± 2.28	31.41 ± 1	55.11 ± 4.9	55.18 ± 0.62	58.38 ± 2.74
Absolute humidity, mg/L	25.62 ± 0.68	18.41 ± 0.52	16.45 ± 0.86	11.79 ± 0.37	20.05 ± 2.23	19.61 ± 0.22	21.49 ± 0.67
AquaVENT Armstrong Heated Humidifier							
	Circuit 1	Circuit 2	Circuit 3	Circuit 4	Circuit 5	Circuit 6	Circuit 7
Temperature, °C	33.8 ± 0	33.34 ± 0.36	33.19 ± 0.56	33.54 ± 0.62	33.38 ± 0.11	33.33 ± 0.07	33.83 ± 0.05
Relative humidity, %	54.64 ± 6.33	72.46 ± 2.86	67.47 ± 2.76	73.35 ± 2.13	65.65 ± 4.02	60.38 ± 6.93	57.23 ± 5.03
Absolute humidity, mg/L	20.49 ± 2.37	26.10 ± 1.28	23.98 ± 1.21	26.91 ± 1.32	23.42 ± 1.52	20.78 ± 3.66	21.46 ± 1.88

Data are presented as median ± SD. Circuit 1: Fisher & Paykel RT202 heater-wire circuit; Circuit 2: Fisher & Paykel Evaqua 2 heater-wire circuit; Circuit 3: Medtronic-DAR heater-wire circuit; Circuit 4: Flexicare heater-wire circuit; Circuit 5: Intersurgical heater-wire circuit; Circuit 6: AquaVENT heater-wire circuit; Circuit 7: GGM heater-wire circuit.

The highest AH values were recorded with the Fisher & Paykel MR850 active humidifier and the Medtronic-DAR circuit (AH = 40.8 mg/L with flow of 50 L/min, $P < .001$). The lowest AH was recorded with the HH and the Flexicare FL9000 circuit (AH = 11.4 mg/L with 100 L/min flow, $P < .001$) (Fig. 2).

The lowest overall performance among the different combinations was observed with the Flexicare FL9000 HH

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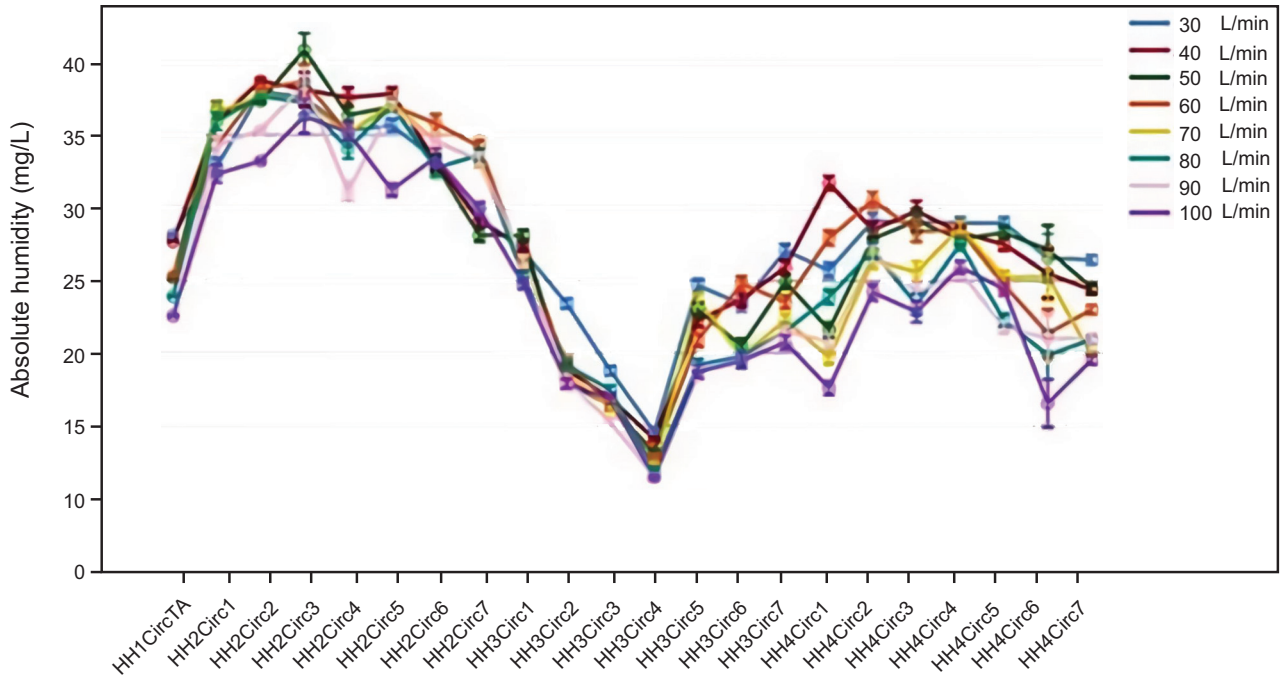

Fig. 2. Absolute humidity delivered by the different combinations of devices and circuits at different flows. HH1: Cloud heated humidifier; HH2: Fisher & Paykel MR850 Heated Humidifier; HH3: Flexicare FL9000 heated humidifier; HH4: AquaVENT Armstrong heated humidifier; CircTA: conventional disposable circuit with water trap; Circ1: Fisher & Paykel RT202 heater-wire circuit; Circ2: Fisher & Paykel Evaqua 2 heater-wire circuit; Circ3: Medtronic-DAR heater-wire circuit; Circ4: Flexicare heater-wire circuit; Circ5: Intersurgical heater-wire circuit; Circ6: AquaVENT heater-wire circuit; Circ7: GGM heater-wire circuit.

combined with the same brand heater-wire circuit, with a maximum AH of 14.5 mg/L at a flow of 30 L/min and decreasing significantly with higher flows ($P < .001$). In contrast, the Fisher & Paykel MR850 HH combined with the Fisher & Paykel Evaqua 2 circuit always delivered AH > 33 mg/L, even with flows of 100 L/min. For flows > 50 L/min, the best performance for all flows in terms of AH was with the Fisher & Paykel MR850 HH, regardless of the circuit used ($P < .001$) (Fig. 3).

Regarding the presence of condensation in the circuits, this was observed when using the Cloud HH with the disposable circuit with water trap and when using the Fisher & Paykel MR850 HH with all of the heater-wire circuits except the Medtronic-DAR circuit. The Medtronic-DAR circuit was the only one in which no condensation was observed independently of the HH used (Table 3).

Discussion

This study provides information on the performance of currently available HH systems used for HFNC, in terms of temperature and humidity delivered. To our knowledge, this is the first study to evaluate flows of up to 100 L/min. We consider it important to evaluate unconventional flow ranges because, although these flows may be poorly tolerated by patients and there is still no evidence of proven benefit, some new mechanical ventilators incorporate them as a possibility within the range of available flow. When comparing the 22 sequences, a statistically significant difference was found in the average of AH for each flow between the different combinations of devices and circuits, and even in several cases less than the minimum recommended for mechanical ventilation (ie, 33 mg/L).[13] While using high-flow gas through a nasal cannula, gas flow passes through the upper airway. Therefore, the heating and humidification function is preserved, so that the gas is inspired at 31°C and is fully saturated with water vapor (ie, 100% RH), which should prevent airway dryness and associated lesions. Hence, starting the HFNC at a lower temperature may be a reasonable clinical approach to take advantage of positive clinical outcomes derived from higher comfort, improved tolerance, and longer application of the noninvasive support.[14]

The best-performing HH in terms of AH exceeded the recommended lower limit with 6 of the 7 circuits used at all evaluated flows. The rest of the HHs, regardless of the flow used, did not reach this minimum value of AH delivered with any of the circuits used.[13] The HH with the lowest performance was far from reaching the recommended AH, in addition to exhibiting significant decreases in performance with increasing flow. The latter, in addition to negatively affecting patient comfort, could impair the function of

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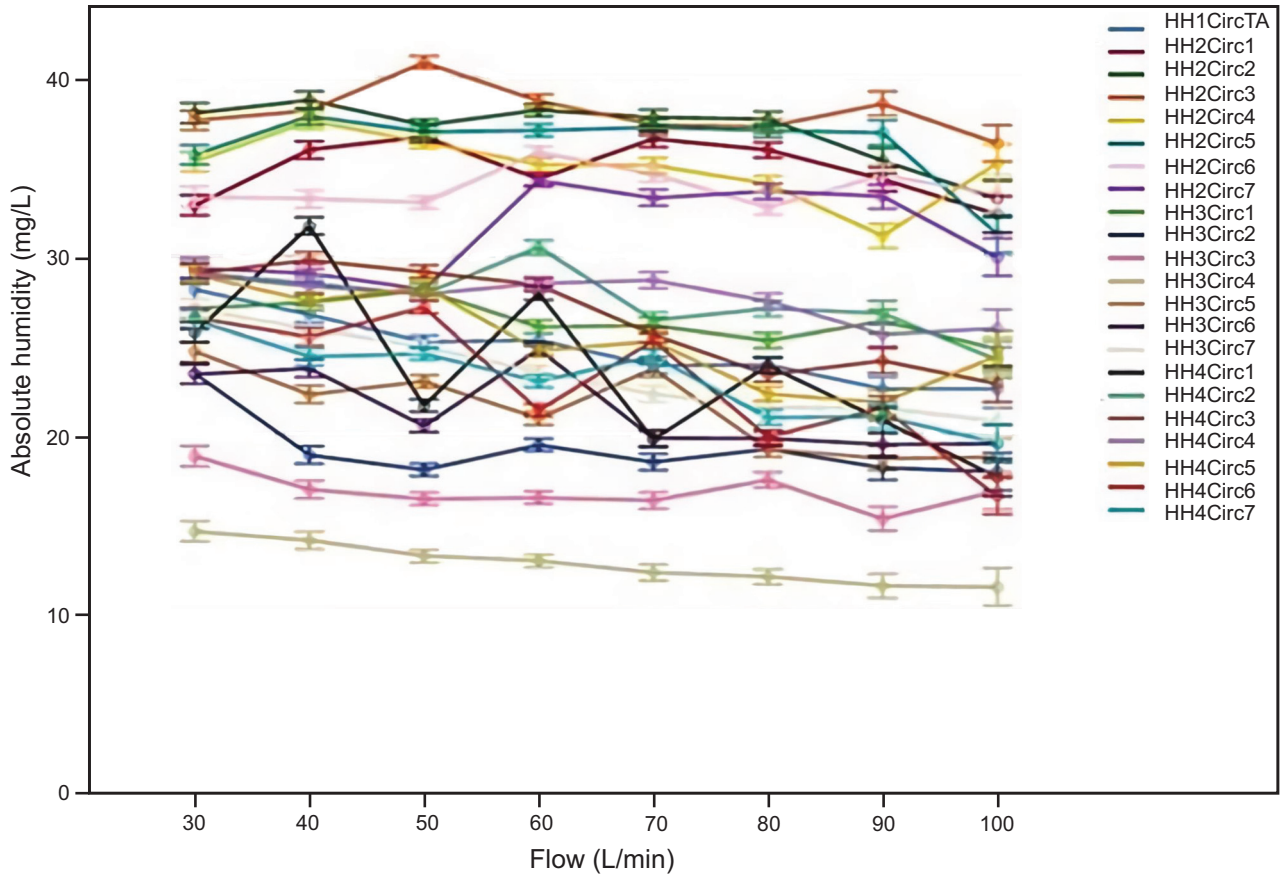

Fig. 3. Absolute humidity delivered at different flows in relation to the different combinations of devices and circuits. HH1: Cloud heated humidifier; HH2: Fisher & Paykel MR850 Heated Humidifier; HH3: Flexicare FL9000 heated humidifier; HH4: AquaVENT Armstrong heated humidifier; CircTA: conventional disposable circuit with water trap; Circ1: Fisher & Paykel RT202 heater-wire circuit; Circ2: Fisher & Paykel Evaqua 2 heater-wire circuit; Circ3: Medtronic-DAR heater-wire circuit; Circ4: Flexicare heater-wire circuit; Circ5: Intersurgical heater-wire circuit; Circ6: AquaVENT heater-wire circuit; Circ7: GGM heater-wire circuit.

Table 3. Presence of Condensation With Different Combinations of Humidifiers and Heated Circuits

Combination HH + Circuit	Condensation	Combination HH + Circuit	Condensation	Combination HH + Circuit	Condensation
HH1CircTA	Yes	NA	NA	NA	NA
HH2Circ1	Yes	HH3Circ1	No	HH4Circ1	No
HH2Circ2	Yes	HH3Circ2	No	HH4Circ2	No
HH2Circ3	No	HH3Circ3	No	HH4Circ3	No
HH2Circ4	Yes	HH3Circ4	No	HH4Circ4	No
HH2Circ5	Yes	HH3Circ5	No	HH4Circ5	No
HH2Circ6	Yes	HH3Circ6	No	HH4Circ6	No
HH2Circ7	Yes	HH3Circ7	No	HH4Circ7	No

HH = heated humidifier; HH1 = Cloud heated humidifier; HH2 = Fisher & Paykel MR850 heated humidifier; HH3 = Flexicare FL9000 heated humidifier; HH4 = AquaVENT Armstrong heated humidifier; Circ1 = Fisher & Paykel RT202 heater-wire circuit; Circ2 = Fisher & Paykel Evaqua 2 heater-wire circuit; Circ3 = Medtronic-DAR heater-wire circuit; Circ4 = Flexicare heater-wire circuit; Circ5 = Intersurgical heater-wire circuit; Circ6 = AquaVENT heater-wire circuit; Circ7 = GGM heater-wire circuit; NA = not applicable.

ciliary epithelium and clearance of secretions, even causing some retention of secretions.[15,16]

In general, the combinations evaluated at the different flows implemented kept the delivery of the temperature stable but not the RH, which could be attributed to 2 phenomena. First, the circuit used could have influenced the RH because the HH managed to keep the temperature stable and thus allowed variation in the RH, and therefore the

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AH could be due to technical issues related to the circuit. Second, the shorter contact time of the gas with the air-liquid interface of the HH chamber as a result of increasing the flow undoubtedly affects the performance of the device. A way to mitigate this effect, besides the method proposed by Chikata et al,[12] could be to increase the contact surface with the use of 2 HHs in series, which, although achievable, could be costly and impractical to implement.

In addition to being the best performer, the combination of the Fisher & Paykel MR850 HH with the Medtronic-DAR circuit was the only setup in which no condensation was recorded during the study. This could be due to the fact that the DAR circuit has a different design from the others, whereby the heater-wire uniformly surrounds the outside of the pipe as an integrated spiral wire, minimizing the influence of the environmental temperature on the flow of gas. Throughout this study, an average environmental temperature of 21.6°C was recorded. According to Chikata et al,[17] at conventional flows (ie, < 60 L/min), the environmental temperature has an influence on the amount of condensation recorded in the circuits, with condensation being significantly greater at 20°C compared to a temperature of 25°C. It should be noted that we only noted condensation with the Fisher & Paykel MR850 HH, probably because it was the device that delivered higher values of temperature and humidity. This characteristic, in combination with circuits with less thermal isolation, could result in condensation even at an unconventional flow (eg, > 60 L/min).

This study has certain limitations, the main one being the fact that it is a laboratory study, so the results obtained must be interpreted with caution in a clinical setting. In addition, although the study was designed to evaluate the performance of devices at different flow levels, a simulation of different ventilation patterns and tidal volume was not performed, so we could not assess their influence on the performance of humidification systems, although there is evidence that invasive mechanical ventilation might not affect the delivery of AH.[18] Also, the use of an F_{IO_2} of 0.21 could be questioned. However, from the point of view of thermodynamic characteristics (eg, specific heat, molecular weight, density), both compressed air and oxygen, and their mixture, have similar behavior.[19] Finally, flows > 60 L/min aren't currently used in clinical practice, so our results should be interpreted with caution in a clinical setting. More studies are needed to evaluate its usefulness in a clinical scenario.

Conclusions

During HFNC oxygen therapy at conventional and unconventional flow ranges, heated humidifiers behave differently, in many cases being inefficient in delivering adequate humidification, even at conventional flows. Caution is therefore recommended when selecting the devices and flows for the implementation of high-flow oxygen therapy.

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