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Evaluation of the humidification performances of new generation of heated wire humidifiers

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Conflicts of Interest: FL received fundings from Fisher & Paykel Healthcare for the development of a free smartphone application (*VentilO*) to promote early utilization of protective mechanical ventilation and from Vincent Medical to conduct the bench study.

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ABSTRACT

Background

At high ambient temperatures in ICU rooms, the humidification performances of heated wire humidifiers (HH) are significantly reduced, with delivered gas humidity well below 30 mgH_2O/L leading to an increased risk of endo-tracheal occlusions, sub-occlusions or mucociliary dysfunction.

The objective of the study was to evaluate the humidity delivered at the Y-piece with new generation HH with advanced algorithm (FP950 and VHB20) while varying ambient temperatures.

Methods

We measured on bench the hygrometry of inspiratory gases delivered by new generation of HH (i) FP950 (Fisher&Paykel Healthcare) (ii) VHB20 (Vincent Medical) and previous generation of HH (iii) MR850 with usual settings (37 at the chamber/40 at the Y piece) (iv) MR 850 with no temperature gradient (40/40), and (v) MR850 with automatic compensation algorithm activated. Hygrometry was measured with the psychrometric method after one hour of stability while varying the room temperature from 20 to 30°C.

Results

Two hundred and ninety-four hygrometric bench measurements were performed at steady state for the different tested conditions. With the new HH (FP950 and VHB20), gas humidity delivered remained above 30 mgH_2O/L in all tested conditions, even at high ambient temperatures (> 25°C). With previous generation of HH (MR850), at high ambient temperature, humidity delivered was adequate in only 26% (11/42) of the measurements when usual settings were used (37/40) and 30% (11/37) with automatic compensation. When no temperature gradient was set (40/40), humidity delivered was above 30 mgH_2O/L in 91% (30/33) of the measurements at high ambient temperature. With ambient temperature below 25°C, almost all devices and settings provided adequate humidity.

Conclusion

The new FP950 and VHB20 heated wire heated humidifiers using advanced algorithms have demonstrated stable performance while varying the ambient temperature by 20-30°C, better than the previous generation of heated humidifiers when ambient temperatures were high.

Keywords: New heated humidifier, Heated humidifiers, Absolute humidity, Psychrometry, Endotracheal tube occlusions.

INTRODUCTION

Proper humidification of the gases delivered to the patients during mechanical ventilation is mandatory [1-3] and was recognized as such in the first publication of mechanical ventilation in 1953[4]. Heated humidifiers (HH) as well as heat and moisture exchangers (HME) are used for this purpose [1, 3]. It has been shown that high ambient temperature and high outlet ventilator temperature are responsible for heated wire HH dysfunction, with absolute humidity delivered well below recommended values, leading to a high risk of endotracheal tube occlusions[5]. When the temperature of the gas entering the humidification chamber is high, the temperature of the heating plate will decrease to maintain the humidification chamber outlet temperature at 37°C according to the working principles[5]. The humidity delivered at the Y-piece is closely related to the heater plate temperature as previously shown[6], consequently every situation leading to high temperature in the humidification chamber (high ambient or ventilator temperature, sun shining directly on the humidifier). During COVID-19 pandemic, high rates of endotracheal tube occlusions have been described with poor performing HMEs and even with HH when not used in optimal conditions [7-12]. Endotracheal tube occlusions were the second cause of unexpected cardiac arrests in mechanically ventilated COVID-19 patients, frequently associated with unfavorable outcome [13]. This complication is related to under-humidification of the gases delivered to patients [14, 15]. It is recommended to deliver to mechanically ventilated patients a gas humidity greater than 30 mgH_2O/L with HME (ISO 9360) and greater than 33 mgH_2O/L with HH (ISO 8185:1997) [3]. This humidity of 33 mgH_2O/L is neither attained with many HMEs [15] nor with heated wire HHs when ambient temperature is high [5].

The HH performances are partially improved with specific settings (increased chamber temperature to 40°C or activation of the compensation algorithm) [5], but these specific settings have limitations. The aim of the study was to evaluate new generation of heated wire humidifiers (FP950 and VHB 20) that add parameters in their algorithm, including sensors for ambient air temperature, inlet chamber temperature and relative humidity with the objective to maintain a stable humidity delivered to the intubated patients whatever ambient temperature and other conditions.

METHODS

We conducted a bench study in our laboratory at the Research Center of the Institut Universitaire de Cardiologie et de Pneumologie de Québec. We measured the hygrometry of inspiratory gases delivered by new generation of heated wire humidifiers (i) FP950 (Fisher&Paykel Healthcare, Auckland, New Zealand) (ii) VHB20 (Vincent medical, Kowloon, Hong Kong) with recommended settings (36°C at the chamber/39°C at the Y-piece) and set at 37°C /40°C and previous generation of HH (iii) MR850 (Fisher&Paykel Healthcare) with usual settings (37°C at the chamber/40°C at the Y-piece) (iv) MR850 with no temperature gradient (40°C /40°C), and (v) MR850 with automatic compensation algorithm activated.

The new humidifiers have advanced algorithm including the ambient temperature (FP950) and the relative humidity measurements (VHB20). However, we do not have other detail on these algorithms. The double heated wire circuits used in this study were the following: Ventilator Dual Heated Circuit kit – ref 950A91J, (Fisher & Paykel, Auckland, New Zealand) for the FP950 and Inspired – ref 51005683, (Vincent medical Manufacturing Co. Ltd, Hong Kong, China) for the VHB20.

We measured relative and absolute humidity of the inspiratory gases with the psychrometric method, as previously described [5, 15]. An ICU Drager V500 ventilator (Draeger medical, Lubeck, Germany) connected to a test lung (Test lung 190 – 1 liter, Maquet Critical Care AB, Solna, Sweden), was set to provide a constant minute ventilation (10 L/min with tidal volume set at 400 ml and respiratory rate set at 25 breaths/min). The laboratory ambient temperature was changed via the thermostat two to three times each study day, with incremental increases of 2 to 3°C to achieve target temperatures between 20 and 30°C. The ambient temperature was kept stable for at least two hours before humidity measurements with tested humidifiers were performed. There was no predefined ambient temperature target program. However, our goal was to achieve comparable average ambient temperatures and an equivalent number of “high” and “low” ambient temperatures with each device evaluated. Therefore, the latest measurements were carried out to achieve comparable ambient temperatures with all tested devices. The ''humidification laboratory'' was designed with the biomedical department to maintain the ambient temperature stable. The ambient temperatures were collected with high precisions thermometers (Duotemp, Fisher&Paykel) and we recorded the heater plate temperatures from the submenus of the MR 850 heated humidifier and FP 950. Several temperatures (ambient, ventilator outlet, humidification chamber inlet and outlet, Y-piece, heater plate) were recorded as previously described[5]. The different temperatures were recorded at the same time as the hygrometric measurements. Hygrometric measurements were performed after 2 hours of steady state using the psychrometric method [5, 15, 16]. We previously measured that after activating the heated humidifiers, stability was achieved within 30 minutes (data not shown), therefore 2 hours steady state is likely to be sufficient. The psychrometer used was the Yokogawa µR10000 psychrometer, the same model that was used in the previous experiments.

In another series of measurements, we recorded ambient temperatures every 30 minutes over several months in ICU rooms in two Quebec City hospitals equipped with air conditioning (see online supplement).

Statistical analysis

Data were expressed using mean±sd to summarize the data. We compared absolute humidity (mgH_2O/L) delivered at the Y piece among the different heated humidifiers (MR850 with different settings, FP950 and VHB20 at different settings). We did these comparisons for all conditions, for ambient temperatures below or equal to 25°C and ambient temperature above 25°C.

The graphical representation of the relationship between heater plate temperature and absolute humidity suggests defining a statistical model using a spline curve to fit the data as the smoothest way. To compare different heated humidifiers over different ambient temperature, a linear model was defined. A fixed factor was associated to the comparison of the six heated humidifiers and the smooth trend for ambient temperature was define as a fixed spline effect varying by humidifiers. Another statistical approach was to split the ambient temperature date into two categories: below or equal to 25°C and above 25°C. Rather than analysing ambient temperature as a continuous variable, it was proposed to analyse this variable as a two-level fixe factor. A two-way ANOVA with an interaction term between the two fixed factors was defined to compare the different heated humidifiers at the two ambient temperature categories. The normality assumption was verified with the Shapiro-Wilk tests using studentized residuals from the statistical model. The graphical representation of marginal linear predictor with studentized residuals suggest the homogeneity of variances. Statistical significance was present with a two-tailed p value < 0.05. Analyses were performed using SAS version 9.4 (SAS Institute Inc, Cary, NC).

RESULTS

294 hygrometric measurements were performed at steady state for the different tested conditions. Fifty-nine to 64% of the measurements were performed at high ambient temperatures (above 25°C) with the different heated humidifiers (Table 1).

When ambient temperatures were below 25°C, almost all measurements were above 30 mgH_2O/L with previous and new generation heated humidifiers. With the new heated wire heated humidifiers (FP950 and VHB20), the mean humidity delivered remained stable above 30 mgH_2O/L of delivered absolute humidity even with ambient temperatures above 25°C. With previous generation of HH (MR850), at high ambient temperature, mean humidity delivered was adequate, i.e. 36.0±3.5 mgH_2O/L, only when no temperature gradient between humidification chamber and Y-piece was set (40/40). With the MR850, when ambient temperature was high, mean absolute humidity delivered was 26.0±4.8 and 29.3±2.5 mgH_2O/L with usual settings 37/40 and automatic compensation respectively (Table 1 and Figure 1).

When comparing the new heated humidifiers, both performed well above 30 mgH_2O/L, whatever ambient temperature from 20 to 30°C, with slightly higher humidity with the VHB20 compared to FP950 (Figure 2). Previous generation of HH (MR850), were markedly influenced by ambient temperature, with progressive reduction of the humidity delivered from 20 to 30°C, especially above 25°C, with usual settings (37/40) and with automatic compensation (Figure 3). With those settings, low humidity was frequent and in extreme conditions (near 30°C of ambient temperature), absolute humidity at the Y-piece was as low as 20 mgH_2O/L. However, when no gradient was set (40/40) with the MR 850, the occurrence of under humidification was not frequent and only happened with very high ambient temperature near 30°C (Figure 3).

Heater plate temperature was related to absolute humidity delivered with different settings of the MR 850 (Figure 4).

Ambient temperature was measured continuously in two ICUs of two different hospitals in Québec city during seventeen months and eleven months. Ambient temperatures above 24°C were present in more than 20% of the time in one ICU room, and temperature above 25°C was found almost 10% of the time in the same ICU room. In other rooms, these temperatures were not rare events and high temperatures did not seem seasonal (see online supplement).

DISCUSSION

This bench study evaluated the impact of ambient temperature on previous and new generation heated humidifiers. The study showed that new generation HH using advanced algorithm, were stable and delivered proper humidification, above 30 mgH_2O/L, even with high ambient temperature. Previous generation HH delivered low humidified gases when ambient temperature was above 25°C, except when specific settings were used (40/40). This is the first study that has evaluated new heated wire humidifiers specifically designed to address their known limitation of reduced humidification performance with high ambient temperatures[5].

The previous generation HH, represented in this study by the MR850, which is likely one of the most used heated humidifiers worldwide, was known for years to have reduced humidification performances in specific conditions leading to high inlet chamber temperature[5]. High ventilator temperatures and high ambient temperature (or even the sun directly on the humidifier) lead to low or very low humidity output. This may explain that among the high rate of endotracheal tube occlusion during the recent pandemic, several cases were related to heated humidifiers [9, 12]. Even in ICU with air conditioning in Québec city, we found that ambient temperature above 25°C was not an uncommon event and is probably related to ICU room expositions. Both ICUs were recent and the air conditioning system had recently been updated and revised during the COVID-19 pandemic[12]. It is likely that in hospitals without an air conditioning system or in other latitudes, the ambient temperatures in the ICUs are even higher.

The minimum absolute humidity to be delivered in mechanically ventilated patients is usually define as above 28-30 mgH_2O/L, depending of the reference method used [7, 15, 17]. Below these levels, there are increasing risk of occlusions [14, 18-20], a late marker of under-humidification or of endotracheal tube sub-occlusions [21-23] or muco-ciliary dysfunction[24]. Main risk factors of endotracheal tube occlusion are the low humidity delivered by the humidification devices [1, 15] or the duration of mechanical ventilation [9, 21]. There is an abundant literature that describes the impact of under-humidification on airway mucosal and mucociliary transport dysfunction and bronchial inflammation [24]. Epithelial dysfunction modifies the properties of the mucus, leading to intraluminal depositions of viscous mucus, reduction of endotracheal diameter and increased tube resistances in a few hours [21-23], or endotracheal tube occlusions after several days [15]. While previous generation heated humidifiers deliver humidity above 30 or even 35 mgH_2O/L when optimal conditions are met, they deliver gas with low or very levels of humidity (below 20 mgH_2O/L) when temperature at the humidification chamber inlet are high[5]. To cope with these limits, two heated humidifiers tested in the present study have been developed with advanced algorithm. The FP950 incorporate additional sensors, including the ambient temperature, and this study demonstrated stability of the humidification performances even when ambient temperature is high. The VHB20 uses an algorithm considering the relative humidity that is measured at the distal part of the inspiratory circuit. While advanced algorithms are developed to overcome the limitations of previous generations of heated humidification, cautious clinical and laboratory evaluations of the new generation devices must be undertaken to detect unexpected limitations of these technologies.

It must be emphasized that to date, there is no data demonstrating better clinical outcomes with heated humidifiers compared to performing HMEs, even in large RCTs comparing these two humidification strategies[25, 26].

Our study has some limitations as the evaluation was a bench study and additional clinical evaluation will be required to evaluate other aspects such as user interface, simplicity to use the devices, presence of condensation in the circuits, robustness and cost-effectiveness of these technologies. Regarding this last parameter, it is likely that these new devices will come with increased costs, but if the proper humidity delivered reduces the duration of mechanical ventilation or severe complications such as endotracheal tube occlusions, these additional costs are acceptable. In addition, the impact of minute ventilation with new heated humidifiers was not evaluated in this study.

CONCLUSION

In conclusion, the new heated wire heated humidifiers FP950 and VHB20 demonstrated stable performances while varying ambient temperature from 20 to 30°C, better than did previous generation of heated humidifiers when ambient temperatures were high. Bench evaluation showed good performances in terms of humidification but clinical evaluations are required to assess the practical utilization and potential issues related to the circuits. There is currently no clinical experience with very high humidity delivered (>40 mgH_2O/L). These data demonstrate the progressive improvement of the technology by the industry in response to clinical concerns[5].

Comprehensive recommendations for the selection of a humidification devices should consider the clinical condition, with the choice of heat and moisture exchangers as first line strategy in many situations and heated humidifier to reduce dead space during protective mechanical ventilation with low tidal volumes (6 ml/kgPBW or below as recommended[3, 27]), and in the case of HME's contra-indications such as the presence of hypothermia or bloody secretions[1]. In addition, the choice of a heated humidifier should also take into account the parameter of the variations of ambient temperature in the ICUs and the risk of high ambient temperature. If there is a high risk of high ambient temperatures, previous generations of heated wire humidifiers should be used cautiously with dedicated settings (low or no gradient between humidifier and Y-piece) and with a specific monitoring[6]. With new generation of heated humidifiers, the risk of under-humidification seems very low in tested conditions and excessive humidity as been described for much higher humidity levels[28].

Clinical recommendations such as turning off humidifiers are not acceptable[29]. Similarly, it is not acceptable that critically ill mechanically ventilated patients experience potentially fatal complications related to under-humidification while both good performing HME and HH are now available, with the only restriction to use these devices properly.

QUICK LOOK

Current Knowledge

Heated wire humidifiers are efficient to warm and humidify gases delivered to patients on invasive mechanical ventilation when optimal condition are met. When ambient temperature or outlet ventilator are high, the heater plate temperature diminished as per working principles of the humidifiers and humidity delivered to patients may not be sufficient, leading to increased risk for endotracheal tube occlusion or sub-occlusion. New heated humidifiers with advanced algorithm have been developed to address this limitation.

What This Paper Contributes To Our Knowledge

This study shows that new heated wire humidifiers with advanced algorithm provide adequate humidification whatever the ambient temperature from 20 to 30°C. As previously shown, previous generation humidifiers have low performances when ambient temperature is above 25°C. We report that high ambient temperatures are not rare, even in an ICU equipped with air conditioning at Quebec city, with a northern latitude.

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Author contributions: P.-A.B. and F.L. contributed to the conception and design of the study, data acquisition, and interpretation of the results. E.R contributed to the data acquisition. F.L. contributed to drafting the manuscript. All authors revised the manuscript for important intellectual content, approved the final version, and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. FL is the guarantor of the content of the manuscript, including the data and analysis.

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FIGURES LEGENDS

Figure 1: Absolute Humidity at different ambient temperatures (above and below 25°C) delivered by previous generation (MR850 at different settings: 37/40, 40/40 and with compensation activated) and new generation heated humidifiers (FP950 and VHB20). The minimum recommended absolute humidity (30 mgH_2O/L) is represented by a red line. *P value < 0.001 for comparisons of absolute humidity values when ambient temperatures were above of below 25°C (two ways ANOVA comparisons). Differences of absolute humidity between new and old generation are statistically significant with P value < 0.001 (multiple comparisons).

Figure 2: Humidification performances of new heated wire humidifiers (VHB20, blue circles and FP950, white circles) with varying ambient temperatures from 20 to 30°C. Each point represents a measurement of absolute humidity with the psychrometric method measured at the Y-piece at steady state for different ambient air temperatures. The red horizontal line represents the minimum humidity expected with heated humidifiers (30 mgH_2O/L). Whatever ambient temperatures from 20 to 30°C, all measurements of humidity were above 30 mgH_2O/L with these humidifiers.

Spline curves for absolute humidity delivered at different ambient temperature for VHB20 and FP950. *Two-way ANOVA comparison for spline relationship.

Figure 3: Humidification performances of previous generation heated wire humidifiers (MR850 set at 37/40 (usual setting), orange circles and MR850 set at 40/40, yellow circles and MR 850 with the compensation algorithm activated, grey circles) with varying ambient temperatures from 20 to 30°C. The red horizontal line represents the minimum humidity expected with heated humidifiers (30 mgH_2O/L). The blue dotted line represents the limit of high ambient temperature (arbitrary defined as 25°C). Each point represents a measurement of absolute humidity with the psychrometric method measured at the Y-piece at steady state for different ambient air temperatures.

When ambient temperature was below 25°C, most humidity measured were above the minimum threshold whatever the MR850 setting. When ambient temperature was above 25°C, absolute humidity below 30 mgH_2O/L was frequent with usual MR850 settings (37/40: 74% of measurements) as well as with advanced settings (40/40: 9%; Automated correction mode: 70%). Spline curves for different settings of the MR850 and ambient temperature. *P value represent the interaction effect between settings and ambient temperature.

Figure 4: Relation between heater plate temperature and humidity delivered with MR 850 and different settings (usual settings 37/40, upper panel) and advanced settings (automode and 40/40, lower panels). Heater plate temperature monitoring provides information on humidity delivered with previous generation heated humidifiers (data obtained with MR 850). When this temperature was above 62°C, 100% of the absolute humidity measured were above 30 mgH_2O/L as previously described. Pearson correlations between heater plate temperature and absolute humidity delivered

Table 1: Absolute Humidity delivered at the Y-piece for previous generation of heated wire humidifiers and new generations (FP950 et VHB20) for ambient temperatures above 25 (AT > 25°C) or below 25 (AT ≤ 25°C). For each heated humidifier and each setting, the number of values of absolute humidity below 30 mgH_2O/L (AH<30 mgH_2O/L).

*P<0.05 for pair comparisons vs. MR850 37/40 (reference humidifier).

	MR850 (37/40)	**MR850 (40/40)**	**MR850 Auto**	**FP950**	**VHB (36/39)**	**VHB (37/40)**
All Ambient Temperatures, n	66	54	62	66	23	23
Ambient Temperature (°C), mean±SD	26.4±3.2	26.4±2.9	26.3±3.0	26.3±3.2	25.5±2.9	26.1±3.1
Absolute Humidity (mgH_2O/L), mean±SD	29.2±5.9	37.2±3.2	31.3±3.6	34.8±1.8	37.0±0.9	39.2±1.1
AT > 25°C, n(%)	42 (64%)	33 (60%)	37 (60%)	39 (59%)	12 (52%)	14 (61%)
Ambient Temperature (°C), mean±SD	28.5±1.8	28.4±1.5	28.4±1.6	28.6±1.6	28.0±1.4	28.1±1.9
Absolute Humidity (mgH_2O/L), mean±SD	26.0±4.8	36.0±3.5*	29.4±2.5	33.8±1.5*	37.4±0.9*	39.8±0.9*
AH<30 mgH_2O/L, n(%)	31 (74%)	3 (9%)	26 (70%)	0	0	0
AT ≤ 25°C, n(%)	24 (36%)	21 (40%)	25 (40%)	27 (41%)	11 (48%)	9 (39%)
Ambient Temperature (°C), mean±SD	22.7±1.3	23.2±1.2	23.3±1.4	22.9±1.6	22.9±1.2	22.9±0.9
Absolute Humidity (mgH_2O/L), mean±SD	34.7±2.5	39.1±1.0*	34.2±3.0	36.3±0.7*	36.5±0.7	38.4±0.9*
AH<30 mgH_2O/L, n(%)	2(8)	0	2(8)	0	0	0

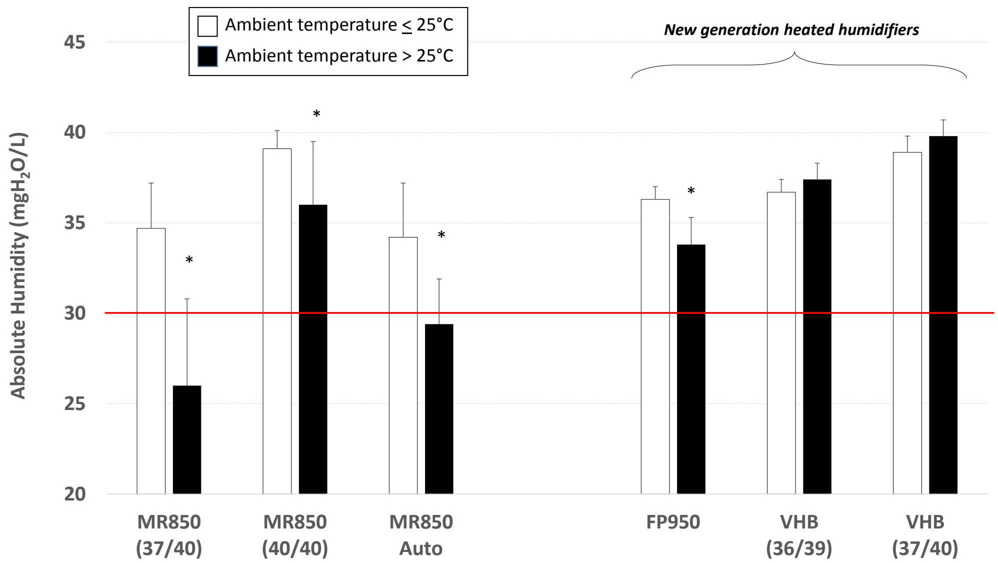


Figure 1: Absolute Humidity at different ambient temperatures (above and below 25°C) delivered by previous generation (MR850 at different settings: 37/40, 40/40 and with compensation activated) and new generation heated humidifiers (FP950 and VHB20). The minimum recommended absolute humidity (30 mgH_2O/L) is represented by a red line. *P value < 0.001 for comparisons of absolute humidity values when ambient temperatures were above of below 25°C (two ways ANOVA comparisons). Differences of absolute humidity between new and old generation are statistically significant with P value < 0.001 (multiple comparisons).

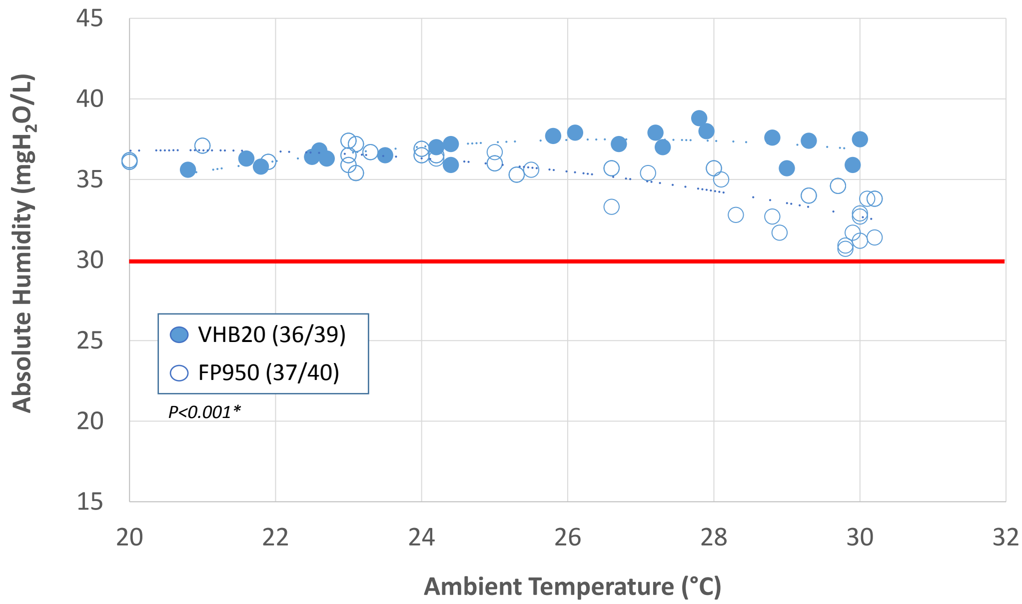
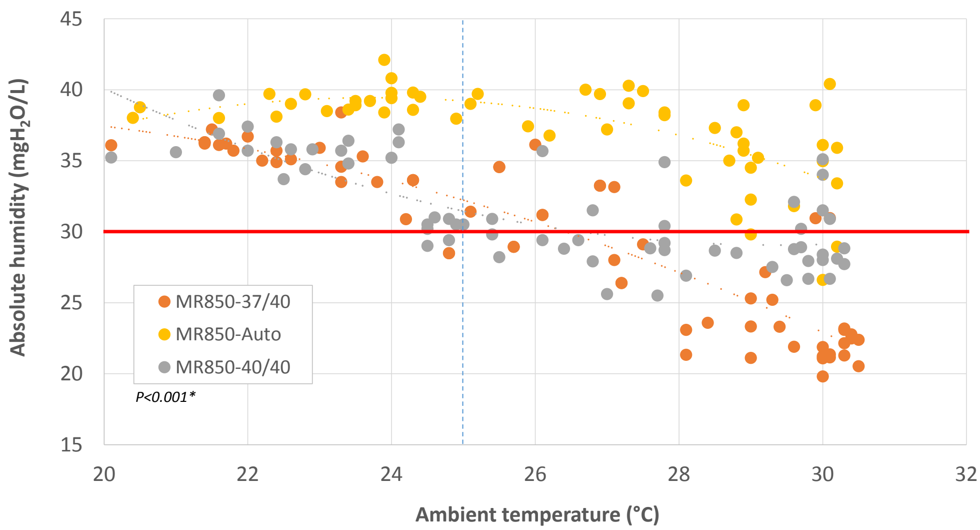


Figure 2: Humidification performances of new heated wire humidifiers (VHB20, blue circles and FP950, white circles) with varying ambient temperatures from 20 to 30°C. Each point represents a measurement of absolute humidity with the psychrometric method measured at the Y-piece at steady state for different ambient air temperatures. The red horizontal line represents the minimum humidity expected with heated humidifiers (30 mgH_2O/L). Whatever ambient temperatures from 20 to 30°C, all measurements of humidity were above 30 mgH_2O/L with these humidifiers.

Spline curves for absolute humidity delivered at different ambient temperature for VHB20 and FP950. *Two-way ANOVA comparison for spline relationship.



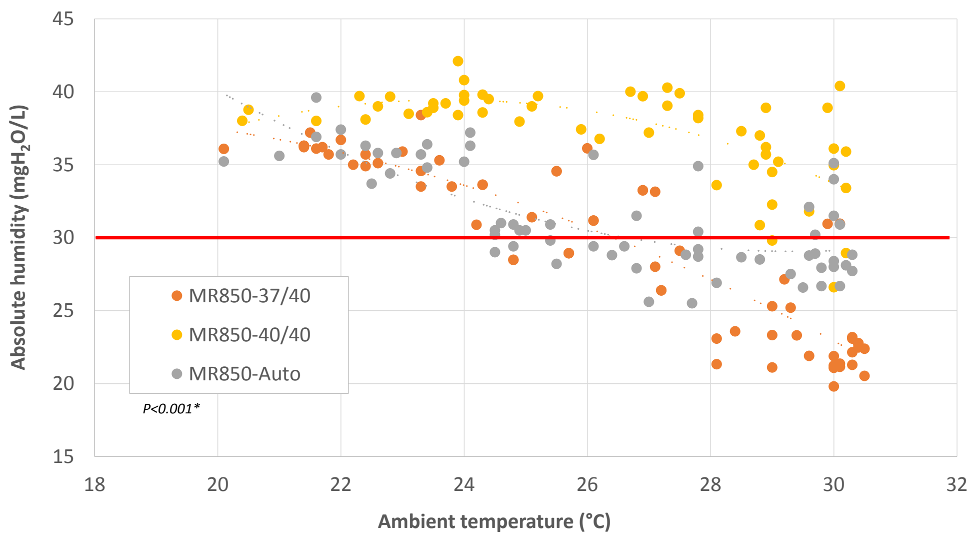


Figure 3: Humidification performances of previous generation heated wire humidifiers (MR850 set at 37/40 (usual setting), orange circles and MR850 set at 40/40, yellow circles and MR 850 with the compensation algorithm activated, grey circles) with varying ambient temperatures from 20 to 30°C. The red horizontal line represents the minimum humidity expected with heated humidifiers (30 mgH_2O/L). The blue dotted line represents the limit of high ambient temperature (arbitrary defined as 25°C). Each point represents a measurement of absolute humidity with the psychrometric method measured at the Y-piece at steady state for different ambient air temperatures.

When ambient temperature was below 25°C, most humidity measured were above the minimum threshold whatever the MR850 setting. When ambient temperature was above 25°C, absolute humidity below 30 mgH_2O/L was frequent with usual MR850 settings (37/40: 74% of measurements) as well as with advanced settings (40/40: 9%; Automated correction mode: 70%). Spline curves for different settings of the MR850 and ambient temperature. *P value represent the interaction effect between settings and ambient temperature.

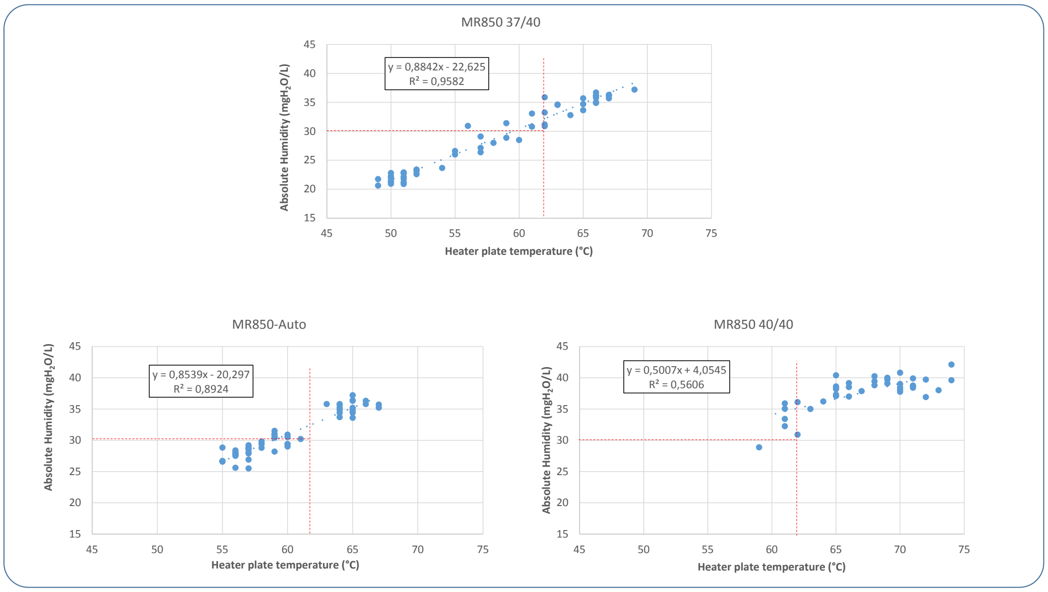


Figure 4: Relation between heater plate temperature and humidity delivered with MR 850 and different settings (usual settings 37/40, upper panel) and advanced settings (automode and 40/40, lower panels). Heater plate temperature monitoring provides information on humidity delivered with previous generation heated humidifiers (data obtained with MR 850). When this temperature was above 62°C, 100% of the absolute humidity measured were above 30 mgH_2O/L as previously described. Pearson correlations between heater plate temperature and absolute humidity delivered at the Y-piece are represented. Coefficient of determination for each relationship are represented.