Measurement of condensed water mass during mechanical ventilation with Heated Wire Humidifiers: experiments with and without pre-warming

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***Abstract*— Heated wire humidifiers (HWHs) are employed in mechanical ventilation with the objective of heating and humidifying the gases delivered to the mechanical ventilator. They use a control based on the adjustment of gas temperature at the chamber outlet. The condensation occurring within the breathing circuit is one of the most important concerns related to this control strategy.**

In the present study we focused on the measurement of the condensation amount within the breathing circuit during the employment of a commercial HWH (MR850, Fisher & Paykel). The measurement of the condensed vapor mass, performed during 7 h of ventilation, provides more objective information than the visual-based scale used in literature. Moreover, two solutions were proposed to minimize the condensation in the breathing circuit tract downward the heated chamber: *i*) a flexible insulating pipe was used to cover the mentioned breathing circuit tract, and *ii*) the air delivered by ventilator was heated before it passes through the chamber at different inlet temperature T_i obtained by employing pre-warming.

To assess the improvement obtained by these two solutions, experiments have been carried out with and without their employment at two minute volumes.

Results show that: *i*) insulation and pre-warming allows minimizing the condensation (e.g., at 8 $L\cdot min^{-1}$ the mass of condensation after 7 h of ventilation decreases from 9.3 g to 2.5 g by using insulation and T_i=27 °C); *ii*) the condensation mass decreases with T_i (e.g., at 8 $L\cdot min^{-1}$ the mass condensation was 2.5 g at T_i= 27 °C and 1.1 g at T_i= 30 °C); and *iii*) the amount of condensation linearly increases with time of ventilation.

I. INTRODUCTION

Mechanical ventilation is required to assist patients in breathing, and, therefore, requires the accurate monitoring of delivered gases parameters, such as flow, relative humidity and temperature [1-4]. For instance, during both non-invasive and invasive mechanical ventilation gases delivered by mechanical ventilator need to be treated –warmed and humidified– along the inspiratory tract of the breathing circuit. This treatment aims for minimizing adverse health effects due to dry gas, particularly critical in neonatal ventilation. The degree and most appropriate method of conditioning is debated –i.e., vapor content higher than 30 $mgH_2O\cdot L^{-1}$ or about 44 $mgH_2O\cdot L^{-1}$ at 37 ◦C [5,6]–. Heated Wire Humidifiers (HWHs) are largely employed to treat gas in long lasting neonatal ventilation. They are placed along the inspiratory tract of the breathing circuit: the gas delivered by mechanical ventilator passes through the water reservoir of the HWHs. The reservoir is placed on a metallic plate heated by Joule phenomenon, which warms the liquid. When the gas passes through the reservoir absorbs the vapor and increases its temperature. The control strategy of HWHs is usually based on the adjustment of the heat lost on the electrically powered plate which aims at maintaining constant the temperature at the chamber outlet (T_{out}). Therefore, the control strategy, called "single point temperature control", employs the measurement of T_{out} as a feedback. Furthermore, HWHs uses a heated wire placed within the breathing circuit tract between the reservoir and the Y piece to avoid a gas temperature decrease along the inspiratory limb. Although, in literature more complex controls have been proposed [7, 8], commercially HWHs employ the aforementioned control which does not allow obtaining sufficient performances under unfavorable conditions: absolute humidity of inspired gas can be much lower than recommended or too high with consequent condensation. The factors which influence HWHs performances are largely studied: gas humidification decreases with T_i [9], is influenced by ventilatory settings [10, 11, 12] and environmental temperature [13]. Among the performances of HWHs, the amount of condensed vapour within the breathing circuit is very important since it can increase the rate of pulmonary infection. Lellouche *et al.* [13] and Ricard *et al.* [14] analyzed the condensation on the wall of the humidification reservoir and on the breathing circuit, respectively, by a visual scale.

In this paper the mass of condensed vapor within the breathing circuit has been measured during ventilation lasting 7 hours, as proposed in a recent study [15]. Experiments have been carried out at two minute volumes, MV, (i.e., 4 $L\cdot min^{-1}$ and 8 $L\cdot min^{-1}$), without pre-warming ($T_i\approx$24°C), with slight ($T_i\approx$27 °C), medium ($T_i\approx$30 °C) and intense pre-warming ($T_i\approx$35 °C), in order to assess the influence of MV and T_i. Furthermore, a flexible pipe insulation was used to insulate the breathing circuit tract downward the HWH in order to minimize the condensation in the breathing circuit tract. Data obtained with and without insulation and with and without pre-warming have been compared in order to assess the improvement obtained by employing these solutions.

II. THEORETICAL BACKGROUND

HWHs present a heater wire along the breathing circuit between the humidification chamber and the Y piece to increases the gas temperature along this tract. This operation

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aims to avoid the vapor condensation because the relative humidity [RH] decreases with temperature. In fact, RH can be expressed as:

$$RH = \frac{1.61 \cdot p_t}{p_s} \cdot AH \tag{1}$$

being p_t and p_s the total gas pressure and the saturation pressure of water vapor, respectively, and AH the absolute humidity.

Since p_s increases with temperature T [16]:

$$p_s = 611.21 \cdot \exp\left(\frac{17.502 \cdot T}{240.97 + T}\right) \tag{2}$$

RH decreases with T. Therefore, the increases of temperature performed by HWHs should prevent vapor condensation. On the other hand, the outer part of the breathing circuit wall is at environmental temperature (20÷25 °C), hence its temperature is lower than the one of the internal gas (i.e., ≈40 °C). Therefore, the temperature increase is not sufficient to overcome the concern related to the condensation, as reported in literature [9,13,15].

III. Experimental Setup

The experimental setup has been proposed in a previous study by the same research group [15]. The gas at two different MV (i.e., 4 $L \cdot min^{-1}$ and 8 $L \cdot min^{-1}$) and at a respiratory frequency of 20 bpm has been delivered by a mechanical ventilator (Servo 300A, Siemens, Fig.1a). The gas reaches the HWH (MR 850, Fisher & Paykel Healthcare, Auckland, New Zealand, Fig.1b) through a standard breathing circuit. The gas temperature at the chamber inlet (T_i) has been adjusted by a manual control of the electrical power dissipated on a heated wire encapsulated in the breathing circuit (Fig.1c). The power has been supplied by a DC voltage generator (Fig.1d) and the value of T_i has been displayed on a digital multimeter equipped with a type-K thermocouple (179, Fluke, range −40°C to 400°C, accuracy ±1 °C, Fig.1e). The HWH (MR850, Fisher & Paykel) employs a temperature sensor to measure the gas temperature at the chamber outlet (T_o), which is used as a feedback to adjust the electrical power lost dissipated on the heater plate of the chamber. This simple control strategy aims at maintaining T_o within 37±1°C. All trials have been performed by selecting the HWH operation mode as 'invasive mode'. In this modality the HWH maintains T_i within 37±1°C and ensures that the Y piece temperature (T_Y) ranges within 40±1°C. This simulates a clinical scenario being the "invasive mode" employed in tracheostomized patients and when their upper airways are bypassed by an endotracheal tube. A value of T_Y higher than T_o is obtained by heating the gases upward the reservoir through a heated wire encapsulated within the breathing circuit (Fig.1f). During some trials, an insulating flexible pipe has been used to cover this tract of breathing circuit. At the end of the Y piece, a lung simulator, which can be employed for tidal volume up to 1 L, (Test Lung 190, Siemens, Fig.1g) was mounted.

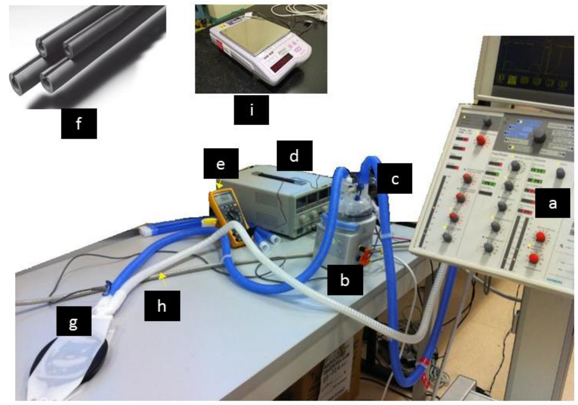

Figure 1. Experimental setup: a) mechanical ventilator; b) HWH; c) breathing circuit upward the chamber; d) DV power supply; e) multimeter; f) flexible pipe insulator; g) lung simulator; h) breathing circuit downward; i) technical balance.

In order to estimate the condensation amount, the mass of the breathing circuit placed between the chamber and the Y piece (Fig.1h) was measured in two phases: *i*) before the start of ventilation (m_o=112.9±0.1 g), when the condensation was absent, and *ii*) during the 7 hours of ventilation, each hour ($m_i(t)$). The mass of condensation, Δm, was estimated as the difference between m_i and m_o, as reported in [15]. All the mass measurements have been carried out by a load cell technical balance (range up to 7500 g, resolution of 0.1 g, EU 7500, Gibertini, Fig.1i). This approach is not operator dependent and allows discriminating small amount of condensation.

IV. Results

The mass of condensed vapor measured during the experiments and at 20 bpm and 8 $L \cdot min^{-1}$, and at 20 bpm and 4$L \cdot min^{-1}$, without insulating pipe and without pre-warming (T_i=24±1 °C) and employing these two solutions is shown in Fig.2.

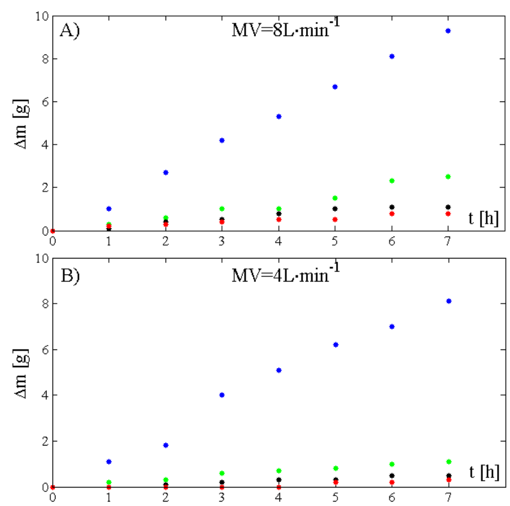

Figure 2. Condensed vapour at 8 $L \cdot min^{-1}$ (A) and 4 $L \cdot min^{-1}$ (B). Blue dots: without insulating tube and without pre-warming (T_i=24 °C); green dots: with insulation and slight pre-warming (T_i=27 °C); black dots: with insulation and medium pre-warming (T_i=30 °C); red dots: with insulation and strong pre-warming (T_i=35 °C).

Data show that the introduction of insulation and pre-warming strongly improve the issue related to the vapor condensation at both the MV: e.g., at 8 L·min^{-1}, after 7 h of ventilation the mass of condensed vapor is about 9.3 g without these solutions *vs* values lower than 2.3 g employing pre-warming and insulation. Moreover, the higher is the pre-warming the lower is Δm (e.g., 2.3 g at T_i=27 °C *vs* 1.1 g at T_i=30 °C).

The experimental data also allow investigating the influence of MV on Δm at the different experimental conditions is reported in fig.3: in all the four conditions the amount of condensed vapor has been higher at 8 L·min^{-1} than at 4L·min^{-1}.

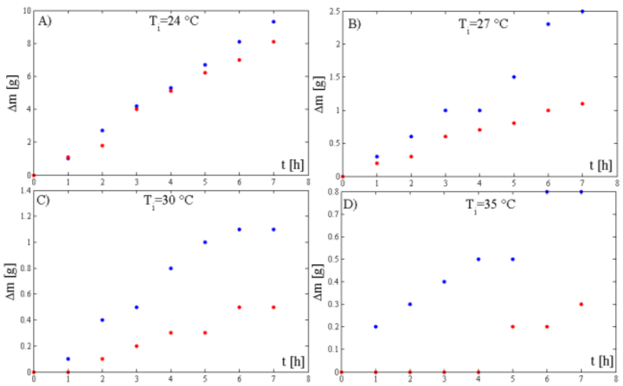

Figure 3. Amount of condensed vapour without pre-warming and insulation (A) and with insulation and different pre-warming intensity (B-D).

The values of Δm measured after the 7 h of ventilation are shown in Table 1.

TABLE I. ΔM AT THE END OF THE TRIALS

	Conditions			
	Without Insulation	With Insulation		
	Ti≈24°C	Ti≈27°C	Ti≈30°C	Ti≈35°C
MV [L·min^{-1}]	Δm [g]	Δm [g]	Δm [g]	Δm [g]
4	8.1	1.1	0.5	0.3
8	9.3	2.5	1.1	0.8

Experimental data show that the mass of condensation increases during ventilation with a linear trend. The best fitting lines for each condition are shown in fig.4.

The high values of R^2 confirm that Δm linearly increases with ventilation time up to 7 h. The slope of the best fitting lines, which represents the mass of condensed vapor per unit of time, shows a marked decrease with the employment of the insulating pipe and with T_i. Furthermore, the slope depends on MV: the bigger the MV the higher the slope (see Table II).

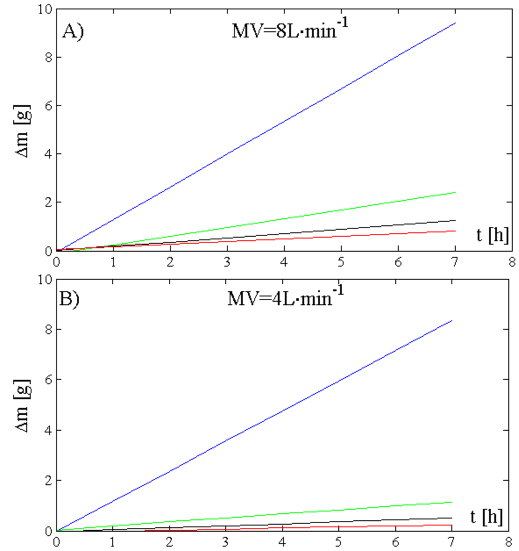

Figure 4. Best fitting lines of the amount of condensed vapour vs ventilation time at 8 L·min^{-1} (A) and 4 L·min^{-1} (B). Blue lines: trials performed without insulating tube and without pre-warming (T_i=24 °C); green lines: trials performed with insulation and slight pre-warming (T_i=27 °C); black lines: trials performed with insulation and medium pre-warming (T_i=30 °C); red lines: trials performed with insulation and strong pre-warming (T_i=35 °C).

TABLE II. BEST FITTING LINES OF THE AMOUNT OF CONDENSED VAPOUR VS TIME OF VENTILATION:SLOPE AND CORRELATION COEFFICIENT ARE REPORTED

	Conditions			
	Without Insulation	With Insulation		
	Ti≈24°C	Ti≈27°C	Ti≈30°C	Ti≈35°C
	MV=4 L·min^{-1}			
s [g·h^{-1}]	1.19	0.165	0.0714	0.0307
R^2	0.987	0.982	0.944	0.651
	MV=8 L·min^{-1}			
s [g·h^{-1}]	1.34	0.338	0.178	0.121
R^2	0.998	0.954	0.962	0.944

V. DISCUSSION

The estimation of condensed vapor through the measurement of the breathing circuit mass allows discriminating slight variation of mass (i.e., <0.1 g). therefore, it has been possible to compare results under different operating conditions, overcoming the well-known concerns related to the use of visual scale (e.g., low resolution, operator dependency…) [9,13].

The quantitative analysis reported in this study has confirmed that the solution employed on HWH, which increases the gas temperature of 3°C between the chamber exit and the Y piece (37°C vs 40°C), is not sufficient to avoid vapor condensation, and that the condensed vapor increases with MV [15]. In fact, at environmental temperature the amount of condensed vapor after 7 h of ventilation is about 9.3 g at 8L·min^{-1} and 8.1 g at 4 L·min^{-1}. This concern becomes particularly important when the ventilation is not carried out in the hospital but in environment where the temperature can experience relevant changes.

In order to improve the performances of HWHs related to the condensation within the breathing circuit, two solutions, which represent the main novelties of this work, are proposed: 1) to carry out a pre-warming treatment to increase the inlet gas temperature. The pre-warming should avoid over-humidification as reported in previous studies [11, 12]; 2) to insulate the wall of the breathing circuit by a flexible insulating wire. This solution aims at avoiding a temperature decrease of the breathing circuit wall due to the temperature difference between the gas flowing through the breathing circuit (i.e., ≈40°C) and the environmental temperature (≈24°C).

Experiments show that the proposed solutions allow minimizing the condensation: after 7 h of ventilation the amount of condensed vapor strongly decreases: at 8 $L\cdot min^{-1}$ from 9.3 g to 2.5 g (T_i=27°C) 1.1 g (T_i=27°C) 0.8 g (T_i=27°C); at 4 $L\cdot min^{-1}$ from 8.1 g to 1.1 g (T_i=27°C) 0.5 g (T_i=27°C) 0.3 g (T_i=27°C). These results are also confirmed by the values of s (Table II): e.g., at 8 $L\cdot min^{-1}$, the mass of condensed vapor per unit of time decreases from 1.19 $g\cdot h^{-1}$ to 0.165 $g\cdot h^{-1}$ employing insulation and slight pre-warming (T_i=27°C).

Summing up, the main findings are: the results obtained by the introduction of the two aforementioned solutions, and the comparative analysis between amount of condensed vapor without these solutions (clinical scenario) and employing the insulation pipe and different intensities of pre-warming.

VI. Conclusion

The results confirm that the gas temperature increase between the outlet chamber and the Y piece does not prevent the condensation along this tract. Moreover, the introduction of a flexible insulating pipe, which avoids the direct contact between the breathing circuit wall and the environmental temperature, allows maintaining high the temperature of the wall minimizing condensation (see Table II). The introduction of the mentioned solution, coupled to the gas pre-warming almost prevent the condensation. A further advantage to perform the pre-warming is to make independent the inlet gas temperature, which strongly influence the HWHs performances, from environmental one. The improvement obtained by employing the two mentioned solutions encourages to perform further trials to investigate their influence at different respiratory settings or during an intra-breath analysis [17].

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