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Performances of heated humidifiers in mechanical ventilation: a preliminary intra-breath analysis

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Abstract— **A correct humidification of gases delivered to mechanically ventilated patients is essential to avoid some complications.**

Heated Humidifiers (HHs) are widely used in long lasting ventilation to treat gases delivered to patients. Their performances depend on some parameters, such as environmental conditions and ventilatory settings. The aim of this work is to experimentally assess the influence of minute volume (*MV*), respiratory frequency (*f*) and the ratio between duration of inspiration and expiration (*I:E)* on HHs performances in terms of relative humidity (*RH*) at the humidification chamber outlet. The main novelty of this work is the assessment of *RH* oscillations during artificial ventilation.

Results show marked oscillations of *RH* during a single breath (ripple of 20 % in the worst case); oscillations decrease if *f* and *I:E* increase, on the other hand they increase with *MV*. Since the variation of gas temperature during a respiratory act can be neglected, the *RH* oscillations are related to the vapour content in the delivered gases.

These results further support the hypothesis which asserts that HHs performances could be improved by using a control strategy taking into account ventilatory settings.

I. Introduction

Gas delivered to mechanically ventilated patients requires to be heated and humidified in both invasive and noninvasive mechanical ventilation. Gas treatment plays a crucial role in the management of critically ill patients influencing prognosis and complications, such as impairment of ciliary function, and hypothermia and accumulation of secretions in airways [1, 2]. The optimal thermo-hygrometric gas conditions are debated and there are different recommendations: 1) at least 30 mgH_2O/L for inspiratory gases [3], or 2) 44 mgH_2O/L, which corresponds to 100% relative humidity (*RH*) at 37 °C [4]. Heated Humidifiers (HHs) and heat and moisture exchangers are the most widely used devices to treat gases in long lasting ventilation. HHs present a water reservoir placed on a heater plate that warms the liquid. Gas delivered from ventilator passes through the chamber absorbing vapour and heat. Some studies investigated the influence of ventilatory settings and environmental conditions on HHs performances. *RH* of gases at the chamber exit decreases with minute volume, *MV*, or tidal volume (*VT*) [5]; on the other hand, at low *MV* or *VT* gases are over-humidified and condensation in the breathing circuit is marked [6]; furthermore, environmental and inlet gas temperature strongly influence HHs performances [7]. Since the adjustment of the heater plate power aims to maintain a constant outlet chamber temperature of gases, the power decreases with both external and inlet chamber temperature causing a decrease of water temperature in the chamber. Consequently, there is an inverse relationship between inlet chamber temperature and *RH* of gases at the exit of the chamber [8]. The influence of these parameters on *RH* at chamber exit, was investigated delivering both continuous [9] and oscillating flows [10]. All these investigations are performed considering a long time interval containing a high number of respiratory acts; therefore the *RH* values reported in the abovementioned studies represent the mean value of *RH* considering several respiratory acts.

To the best of our knowledge there are no previous studies in literature in which *RH* is continuously monitored and the amplitude of its intra-breath oscillations is assessed.

The aim of this work is twofold: 1) to monitor intra-breath oscillations of *RH*; 2) to assess the influence of *MV*, of the ratio between duration of inspiration and expiration, *I:E,* and of respiratory frequency, *f*, on the amplitude of these oscillations. These three ventilatory parameters are set in order to cover the most commonly used values applied in mechanical ventilation.

This intra-breath analysis could be useful to perform a deep investigation of some effects related to an incorrect gas humidification, such as condensation on the wall of the breathing circuit, and to improve the HHs control strategies.

II. Theoretical Background

The content of vapour in air can be described in terms of absolute humidity (*AH*) and *RH*. *AH* is defined as the vapour contained in a certain volume of air; thus, it is usually expressed in mgH_2O/L. More often, studies regarding humidification process in mechanical ventilation consider *RH*, which can be expressed as follows:

$$RH = 1.61 \cdot \frac{P}{P_s(T)} \cdot AH \qquad (1)$$

where P and $P_S(T)$ are the total pressure of the gas and the saturation pressure of vapour at gas temperature, T, respectively. As it well known, $P_S(T)$ increases with gas temperature [11] accordingly to the following equation:

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

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Therefore, by considering a constant *P*, the value of *RH* depends on the vapour content of air mixture and decreases with *T*.

III. METHODS

A. Experimental setup

In order to evaluate the influence of *MV*, *f*, and *I:E* on *RH* oscillations, a HH (SCH 1000 plus, Ginevri srl) was tested (Fig. 1A). Air delivered by a ventilator (Servo Ventilator 900C, Siemens, Fig. 1B) was conveyed within the humidification chamber of the HH through a hose of a standard breathing circuit (Fig. 1C). At the chamber outlet a humidity sensor (HIH-4010, Honeywell International Inc., Morristown, NJ, USA: range from 0% to 100% and accuracy ±3.5%, Fig. 1D) was placed to monitor outlet relative humidity, RH_{out}, of gases. Its voltage output was displayed on a digital oscilloscope (WaveAce 214, LeCroy, New york, USA, Fig. 1E). Outlet gas temperature, T_{out}, was monitored by type K thermocouple (Fig. 1D), whose output was acquired by SCXI 1303 (National Instrument, Fig. 1F) of the chassis SCXI 1000 and displayed on a PC (Fig. 1G).

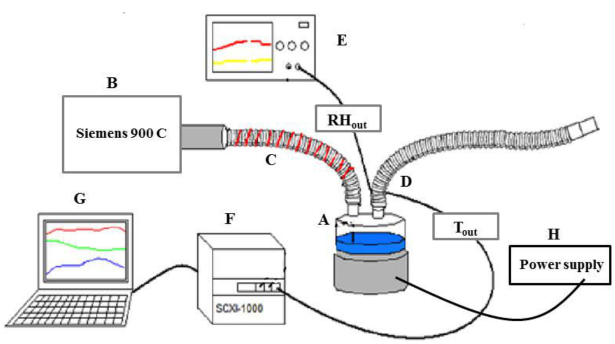

Figure 1. Schematic representation of the experimental setup: A) HH; B) mechanical ventilator; C) breathing circuit; D) outlet of the chamber where the thermocouple and the RH sensor are placed; E) oscilloscope; F) module to acquire the thermocouple's signal; G) PC; H) power supply unit.

A power supply unit (DCIPS2302A, ISO-TECH – UK, Fig. 1H) was used to heat the plate of the HH aiming to warm the water; it was regulated in order to adjust RH_{out} at a values around 85% to avoid the saturation of *RH* sensor.

B. Ventilatory settings

Experiments are carried out to investigate the influence of ventilator settings on the intra-breath oscillations of RH_{out}, ΔRH_{out}, expressed as the difference between the maximum and the minimum value of *RH* in a single respiratory act. These experiments are performed by delivering gases at different values of *MV*, *f*, and *I:E* in synchronized intermittent mandatory ventilation (SIMV) mode. The ventilatory settings are reported in Fig. 2.

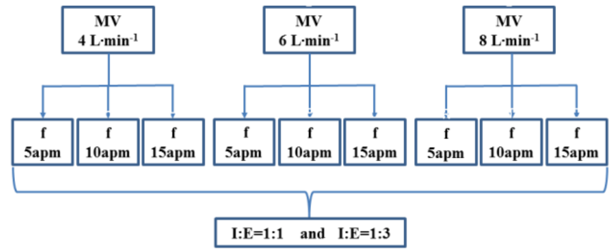

Figure 2. Ventilatory settings used during trials

The values of *MV*, *f* and *I:E* used in this work (Fig. 2), cover a large part of ventilatory settings used in clinical practice.

IV. RESULTS

During all trials, the amplitude of T_{out} intra-breath oscillation (ΔT_{out}) was lower than 0.2 °C. By applying (1) and (2), *RH* variation due to ΔT_{out} of ±0.2 °C was estimated; it can be considered negligible, being lower than 1%. This result allows to assert that the ΔRH_{out} amplitudes measured during trials are only related to vapor content changes in the gas. Therefore we focused our investigation presented below on the monitoring of intra-breath oscillations of *RH*.

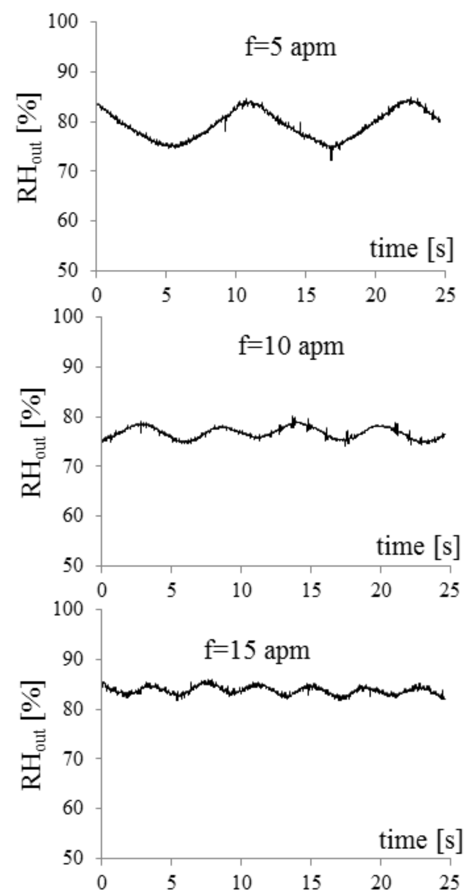

Figure 3. ΔRH_{out} as a function of time at the three different *f*. The other ventilatory settings were *MV*=4 L·min^{-1} and *I:E*=1:3.

Three measurements are carried out for each one of all eighteen ventilatory settings reported in Fig. 2. During all trials, the voltage output of the humidity sensor was sampled at a frequency of 1000 Hz. The calibration curve of the humidity sensor, provided by the manufacturer, was used to calculate *RH* values from the voltage output.

The trends of RH_{out} represented in a time interval (25 s) containing some respiratory acts, at MV=4 L·min^{-1}, $I{:}E$=1:3 and at the three f (i.e., 5 apm, 10 apm, and 15 apm) are reported in Fig. 3, in order to spotlight the influence of f on ΔRH_{out}.

Fig. 3 shows that RH_{out} presents periodic oscillations of period (T_O) equal to the respiratory period (T_r) at f=5 apm (T_r=12 s), T_O is longer than the period shown by the oscillations at f=10 apm (T_r=6 s); at f=15 apm (T_r=4 s), T_O shows a further decrease (≈4 s). The decrease of ΔRH_{out} amplitude with f increase also emerges from Fig. 3 (e.g., at f=5 apm is slightly lower than 15 %, at 15 apm is about 2%).

Aiming to illustrate the influence of MV on ΔRH_{out}, in Fig. 4 are reported the oscillations at f=5 apm, $I{:}E$=1:3, and at the three *MVs*.

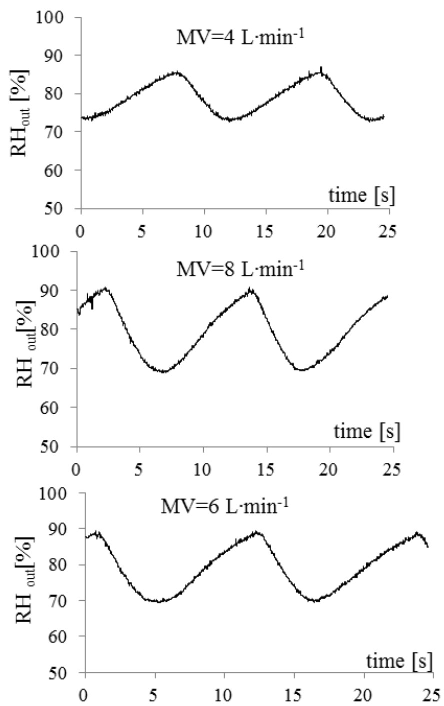

Figure 4. RH_{out} as a function of time at the three different *MV*. The other ventilatory settings were f=4 apm and $I{:}E$=1:3.

The three trends in Fig. 4 present similar period, as expected because T_r is 12 s during the three trials. It is also evident an increase of ΔRH_{out} with MV (e.g., at 4 L·min^{-1} is almost 15 %, at 8 L·min^{-1} is higher than 20 %).

In Fig. 5, the influence of $I{:}E$ on ΔRH_{out} is spotlighted (MV=4 L·min^{-1}, f=5 apm). The amplitude of ΔRH_{out} is also influenced by $I{:}E$ (e.g., at $I{:}E$=1:1 it is about 8 %, at $I{:}E$=1:3 it increases at 14%).

Figures 3, 4 and 5 show that the amplitude of ΔRH_{out}, calculated by considering twenty respiratory acts, decreases with f, on the other hand, it increases with MV and $I{:}E$.

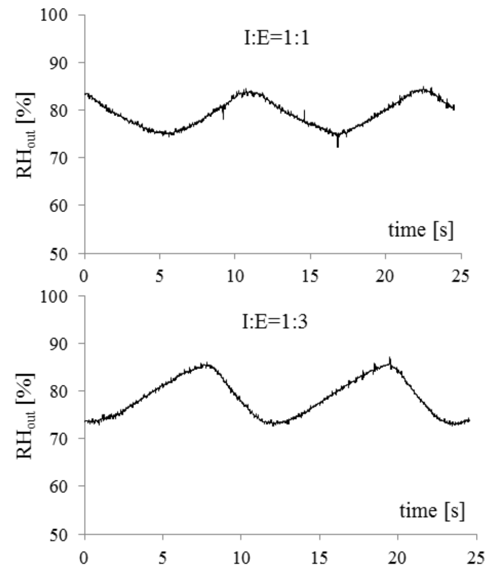

Figure 5. RH_{out} as a function of time at the two different $I{:}E$. The other ventilatory settings were f=4 apm and MV=4 L·min^{-1}.

As way of summary, all these values are reported in Fig. 6; they are represented as the mean ± the expanded uncertainty. The mean was calculated by considering peak to peak difference of *RH* in twenty respiratory acts for three repeated trials. The uncertainty is calculated considering a coverage factor ≈2, corresponding to a confidence level of 95% [12].

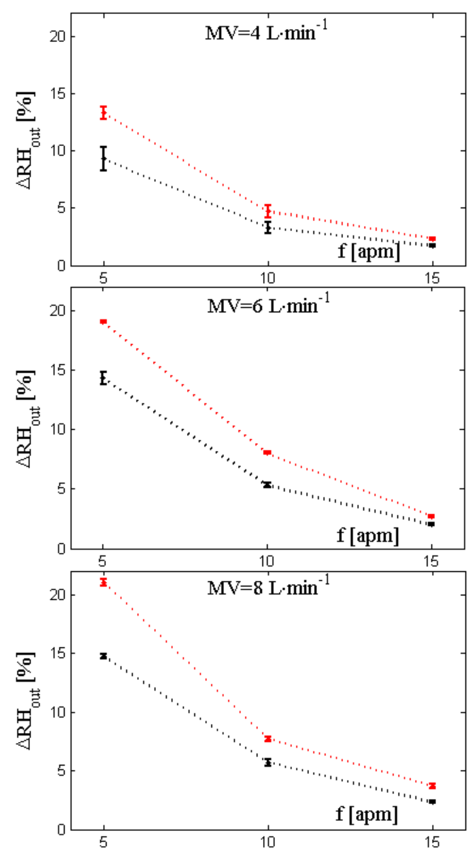

Figure 6. ΔRH_{out} as a function of f at all the three *MV* used during the trials (4 L·min^{-1}, 6 L·min^{-1}, 8 L·min^{-1}). Red dots: experiments performed at $I{:}E$=1:3; black dots: experiments carried out at $I{:}E$=1:1.

As shown in Fig. 6, the amplitude of ΔRH_{out} cannot be considered negligible, in particular at low *f* and high *MV*; in the worst case (*MV*=8 L·min^{-1}, *f*=5 apm, *I:E*=1:3), ΔRH_{out} is about 22 %. Moreover, ΔRH_{out} dependence with *MV* is more marked at 5 apm and 10 apm: e.g., at *f*=5 apm it increases from 14 % to 22 % varying *MV* from 4 L·min^{-1} to 8 L·min^{-1}.

V. Discussion

In literature, several Authors reported the performances of HHs. Most of them analyzed the gas humidity after HH treatment and the influence of both environmental and ventilatory parameters on it. All these studies analyzed the humidity by averaging its value on a large number of respiratory acts: among others, Pelosi *et al.* evaluated *RH* at "Y" piece on ten acts [13], Nishida *et al.* evaluated *RHout* considering five acts [5], Allan *et al.* measured *AH* considering a mean value on 1 hour [14].

In this work the oscillations of *RH* at the chamber outlet, caused by the intermittent flow delivered during mechanical ventilation, are monitored. Since outlet gas temperature oscillations were negligible during all trials, the vapour content variation can be considered the only cause of ΔRH_{out}.

The influence of ventilatory settings on the amplitude of ΔRH_{out} have been assessed. Results show that: 1) the higher is *MV* the higher is ΔRH_{out}; 2) the amplitude of ΔRH_{out} increases when *f* decreases; 3) also *I:E* influences ΔRH_{out}; finally, 4) the oscillations cannot be considered negligible reaching values higher than 20%.

This intra-breath assessment provides a more detailed analysis about the gas treatment rather than an analysis based on the calculation of the mean value of *RH* on a large number of acts. This deep description could explain some effects related to an incorrect humidification, such as, the formation of condensation in the breathing circuit. This phenomenon should also happen if gases reach the patient with a mean *RH* close to an ideal one, but in a part of the act the gas are saturated.

For example, in their valuable work, Nishida *et al.* [5] show that the influence of *I:E* on *RH* value averaged on five acts is negligible; on the other hand, our intra-breath analysis has shown the influence of *I:E* on *RH* oscillations. This finding could be useful to explain a possible relationship between *I:E* and the amount of condensation during ventilation.

Lastly, the description of humidification process which takes into account also an intra-breath analysis of the gas thermo-hygrometric conditions, could provide useful information to improve the control strategies of the HHS.

VI. Conclusion

The *RH* oscillations at the chamber outlet were analyzed at different *MV*, *f*, *I:E*, covering the most widely used settings used in clinical practice.

This analysis shows that the oscillations are not negligible: they increase with *MV* and *I:E* and decrease if *f* increases; in the worst case the oscillations reach an amplitude higher than 20 %. These considerations allow to assert that also when the mean value of *RH* in a large number of respiratory acts is close to the ideal value, during a single breath *RH* reaches values too low or too high. Further research must be performed to evaluate the influence of these oscillations on some critical effects caused by uncorrected humidification, such as condensations on the wall of breathing circuit or other effects due to under-humidification.

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