Improved Portable Measuring Device for Real-Time Humidity and Temperature Monitoring in Intensive Care Unit

Sarah Tonello, Michela Borghetti, Emilio Sardini, and Mauro Serpelloni

Real time monitoring of temperature and humidity of the air conditioned by Heat and Moisture Exchangers (HMEs) and delivered to patients in intensive care units (ICU) is highly demanded by physicians. As demonstrated by recent literature, only in vivo monitoring of HMEs performances with compact portable measuring systems suitable for ICU routines could provide reliable results. One of the main challenges for these devices is represented by the response time of the integrated temperature and humidity sensors. Long response times might introduce delays and thus make it impossible to follow the actual parameter variation in real time during each breath. In order to overcome this issue, innovative commercial ultra-fast sensors for temperature and humidity monitoring have been properly integrated and characterized in a portable wireless system for in vivo HME monitoring. Tests were performed in laboratory under static and dynamic settings. Response times at 36.8% of about 32 ms and 155 ms were obtained, respectively, for temperature and for humidity sensors. An improvement respect to available devices was thus obtained, achieving a proper monitoring of humidity variations up to 35 acts/minute with a maximum error of 5%. Considering the typical range of respiratory frequency monitored in the ICU, these results make the system suitable for real time evaluation of air conditioning during mechanical ventilation, combining the portability required for integration in the ICU routine with measurement accuracy.

Challenges and Requirements for Respiratory Monitoring

An increasing interest has been recently addressed to the monitoring of respiratory variables during a variety of applications, including occupational, domestic and clinical settings [1]. Among the most recent devices presented, portability, real time continuous monitoring and miniaturization represent the most appealing features both for applications outside [2], [3] and inside the hospital [4]. Focusing on the clinical environment, these requirements become more crucial when dealing with Mechanically Ventilated (MV) patients in Intensive Care Units (ICU). There, continuous non-invasive accurate evaluation of humidity and temperature of the air provided is essential to prevent complications possibly caused by inadequate air conditioning, including functional deterioration of nasal mucosa or pneumonia risk. Passive humidifiers, referred to as Heat and Moisture Exchangers (HMEs), are the filters commonly employed in clinical practice to achieve proper air heating and humidification. They act by retaining heat and part of the water content (at about 32 °C and 100% relative humidity (RH)) from the gas exhaled by the patient and then bringing it back to the patient through the gas mixture delivered by the ventilator [5].

HMEs are simple filters working without any need of external power; thus, a feedback regarding their performances can only be obtained by a proper integrated sensing system. HMEs performances are commonly assessed using a standard in-vitro procedure (UNI 9360-1) performed in laboratory before their commercialization. However, as highlighted by the clinical guidelines of the American Association of Respiratory Care (AARC), an accurate and realistic monitoring of these devices can be only obtained in vivo during HMEs functioning. This would allow the system to properly consider all of the influencing factors such as patient's general condition, environmental conditions and gas volume [6]. Currently, temperature and humidity of artificial air delivered to MV patients in vivo are usually only monitored with sensors in the breathing tubing far from the patient [4]. Due to the cooling effect of the air flux from the ventilator and the distance from the airways, this does not provide an actual and real time measurement of temperature and humidity of the air delivered into the lungs [7]. Thus, one of the main challenges for improving the monitoring of conditioned air to MV patients is to achieve an in-situ online temperature and humidity measurement with a device compatible with ICU practices.

The interest in designing portable devices for monitoring HMEs performances in vivo have been addressed since the late 1990s. The first example was presented by Ricard *et al*. [8] who performed hygrometric measurements for evaluating HME performances throughout a long-term interval (7 days). Only measurements at discrete time points were performed,

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without continuous monitoring during breathing. Alternative approaches were then presented that researched the continuous monitoring of T and RH. Zuur *et al*. [9] evaluated in vivo the humidity of air sampled from the trachea with an external sensor, reaching response times (at 36.8%) < 0.2 s for T and < 0.5 s for RH. This approach, however, was limited due to non-portability and difficult control of sensor positioning, with possible effects on the accuracy (around 5%). Castro *et al*. [10] proposed then an interesting electronic digital thermo-hygrometer for in vivo measurements. The accuracy obtained (2% for RH and 0.5 °C for T) and response times (1.4 s for 90% RH response and 150 ms for 90% T response) allowed the system to perform accurate continuous monitoring of both parameters but with uncertainties introduced at respiratory rates higher than 30 acts/min. Finally, in [11], both T and RH were monitored within the nasal cavity, obtaining very good accuracies (0.1 °C and 0.1%) and response times of 0.5 s for T and 2 s for RH. The main limitation was related to the narrow airway passage in the complex geometry of the nasal cavity, possibly affecting the repeatability of the measurements.

In summary, all of the approaches presented highlighted two key design points to be addressed: sensor response times, to allow real time monitoring even for faster respiratory rates frequent in the ICU (>30 acts/min); and portability, to allow integrability with the clinical routine. In this light, aiming to combine sensor performance with a design compatible with the ICU routine, in [12] a portable, low power, wireless monitoring system for temperature (T) and relative humidity (RH) measurements in vivo during MV through HME have been presented. Clinical tests proved the feasibility of the system within the ICU environment for evaluation of an HME throughout its lifetime. However, software-based analyses highlighted an uncertainty of the recorded measurement with respect to the in vivo values, with errors in detecting the actual value varying from 3% to 30% for respiratory rates between 9 and 27 acts/minute. This uncertainty due to sensor inertia introduces a limitation in term of the range of respiratory rates that are properly monitorable, in agreement with other recent literature findings [4].

An attractive solution to overcome this limitation is the integration of innovative fast sensors (e.g., printed, nanostructured) into portable devices, to combine performances with portability [1]. In this light, the specific aim of this paper was to increase the accuracy of the quantitative evaluation of the HME performances by using faster humidity sensors and setting their optimal position. Starting from the device presented in [12], we addressed here an improvement in terms of accurate and real time monitoring of the measured parameters, focusing on how sensors with shorter response times could improve the reliability of HMEs' monitoring. We focused on the characterization of two innovative ultra-fast printed flexible T and H sensors from Brewer Science (BS), properly integrated in an improved version of the portable measuring system presented in [12]. Through ad-hoc setups, sensor performances both under static and under dynamic conditions have been analyzed under different conditions and compared with the ones of the previous installed sensors. This effort aimed to demonstrate how a proper integration of novel ultra-fast commercial sensors into wireless portable devices could extend the range of monitorable respiratory parameters, making these measuring systems of general interest for the clinical routine.

Portable Device Description

The proposed device consists of two modules positioned before and after HME filter (Fig.1). The device operates independently of the mechanical ventilation system without interfering or altering the patient ventilation. The two modules are called the Display Module (DM) and the Measuring Module (MM). The latter monitors and transmits the sensor data to the DM by a Bluetooth Low Energy (BLE) system. The DM receives the data from sensors (T and RH) and it calculates absolute humidity (AH) and other parameters.

The MM (Fig. 1) is composed of: a sensor block; a conditioning block that contains the optimized circuit for acquiring sensors data; a 16-bit microcontroller commercialized by Microchip for managing the device; a power block with a Lithium 3.7 V battery; a voltage controller TPS71533-Q1, allowing a stable output at 3.3 V; a battery monitor to evaluate power consumption during device functioning; and a transmission block able to send the data via Bluetooth 4.0.

Focusing on the sensor block, where the ultra-fast sensors from BS have been integrated, two subsections can be highlighted, corresponding to two measuring points, respectively, before and after the HME. T and RH are measured on the machine side (before the HME). On the patient side (after the HME), only T is monitored, since while exhaling, the air is almost saturated with water content (100% RH) and inhaling is about 98% RH [13].

The portable device is tiny and light (the machine side board is 60 mm x 45 mm x 27 mm, and the patient side board is 40 mm x 20 mm x 10 mm). The two sections are connected via a 10-pole flat cable. The weight of the measuring module is about 80 g.

Sensors Properties and Conditioning

Sensors mounted in this new version of the device are: a Resistive Temperature Detector (RTD) from BS on the patient and machine side; a resistive H sensor from BS (H); and a T-RH sensor (HYT 271) from Innovative Sensor Technology on the machine side.

The RTD (substituted for the Pt1000 in the old version) is a printed resistive flexible metal-based sensor, specifically designed for enabling accurate, real-time responses to small T variation (accuracy of 0.6 °C, tolerance of ±10%).

The H sensor (Inflect™ sensor) is an innovative carbon-based resistive ultra-fast sensor (response time < 10 ms, resolution < 1% RH and a tolerance of ±10%) developed using printed electronics. Due to the form flexibility, it can be easily integrated in any device and it is optimal for application in breath monitoring where both velocity and accuracy are required.

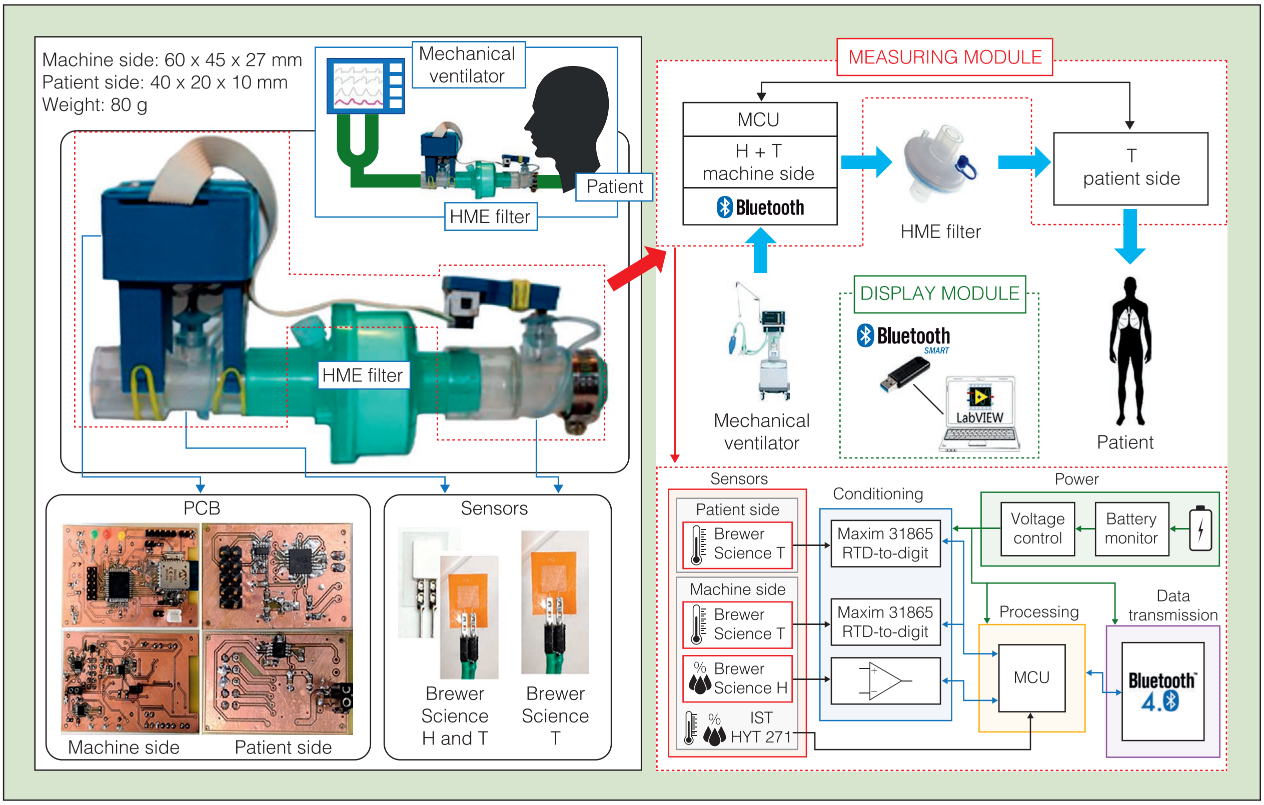

Fig. 1. Detailed picture and schematic representation of the portable device, and block diagram of the MM.

The HYT 271 (already present in the previous version described in [12]) was kept as a reference for comparing RH measurements (accuracy ±2% RH at +23 °C (0% RH to 90% RH) and ±0.2 °C (0 °C to +60 °C) reproducibility ±0.2% RH and ±0.1 °C).

While the HYT 271 already includes integrated electronics for the conditioning of data, both of the new sensors required additional conditioning blocks to digitalize and process measured data. More in detail, the H sensor was conditioned using a customized circuit, placing the sensor in a Wheatstone bridge, and amplifying the output differential voltage using a rail-to-rail instrumentation amplifier (INA826). Differently, the RTD was conditioned directly using an integrated converter from resistance to digital, specifically designed for RTD (MAX 31865 from Maxim). An external resistor was used to set the sensitivity of the RTD and ADC with delta-sigma precision (15 bit) to digitize the ratio between reference and RTD. In order to allow the communication between the different devices and the correct conversion of the data, both sensor conditioning circuits were then interfaced with the PIC24 microprocessor.

Sensors Characterization

Sensors Static Characterization

The static characterization of the two sensors was performed by evaluating the steady state response of the sensors to steps of T or H, controlled using two climatic chambers: a Perani UC 150/70 for T sensor and an Angelantoni MTC120 for H sensor. The reference sensors used were a Pt1000 and the HIH-3610-1 capacitive H sensor from Honeywell with a repeatability ±0.5% RH an accuracy of about ±2% RH, a stability of about ±1% RH and a linearity of about ±0.5% RH.

Temperature sensor static characterization was performed by introducing sensors in the climatic chambers and reading measurement with two multimeters Tektronix DM2510G placed outside. Using an IEEE 488 bus, the two DM2510G were connected to a PC, and the whole measurement procedure was controlled with an own-written LabVIEW VI. Steps of 5 °C degrees were generated in a range of T between 10 °C and 45 °C, allowing 30 minutes for each step to let the T reach a steady value. Twenty measurements were collected for each condition to calculate the average and standard deviation.

The measurement performed with the novel RTD showed a high accuracy, with standard deviation lower than the ones obtained with the Pt1000 (Table 1). Furthermore, data fitting showed a very good linearity (R^2= 0.999972).

Humidity sensor static characterization was performed inside a humidification environment in the climatic chamber, interfacing sensors with two multimeters (Tektronix DM2510G) and a PC, where it was possible to read real time RH values, thanks to a customized LabVIEW interface using the equation reported in the datasheet of the reference sensor from Honeywell.

H steps of 10% RH were then generated in a range between 10 and 70% RH, keeping T constant at 20 ± 0.5 °C.

Nominal T (°C)	Pt1000 (Ω)	RTD Brewer Ω
10	1038.8 ± 0.1	240.5 ± 0.0
15	1057.4 ± 0.1	244.2 ± 0.1
20	1076.2 ± 0.1	248.1 ± 0.1
25	1096.3 ± 0.2	252.3 ± 0.2
30	1114.9 ± 0.6	256.0 ± 0.2
35	1134.5 ± 1.3	260.1 ± 0.2
40	1153.7 ± 0.0	264.0 ± 0.0
45	1171.4 ± 0.0	267.7 ± 0.0

Table 1 – Resistance values from Pt1000 and RTD from BS for increasing T steps

%RH Chamber	%RH	Sensor Brewer Ω
0	7.5 ± 0.5	12514.9 ± 11.2
10	17.4 ± 0.6	12689.8 ± 1.6
20	27.2 ± 0.2	12827.2 ± 2.6
30	36.5 ± 0.3	12935.5 ± 1.9
40	45.8 ± 0.2	13032.5 ± 2.7
50	55.0 ± 0.4	13140.9 ± 3.6
60	64.4 ± 0.2	13271.1 ± 5.1
70	74.2 ± 0.4	13438.8 ± 11.2

Table 2 – Comparison between Honeywell and BS sensor outputs for increasing H steps

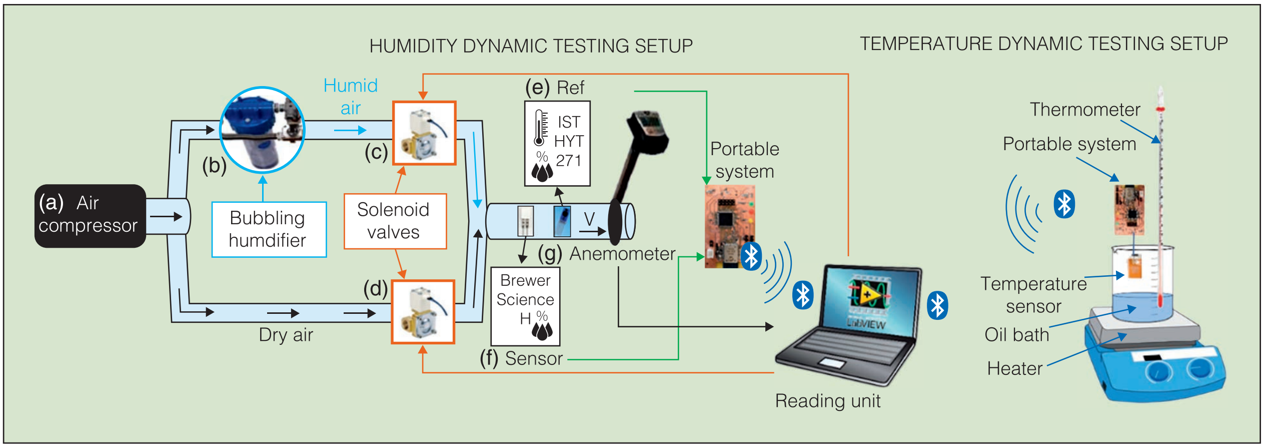

Fig. 2. Dynamic tests setup scheme.

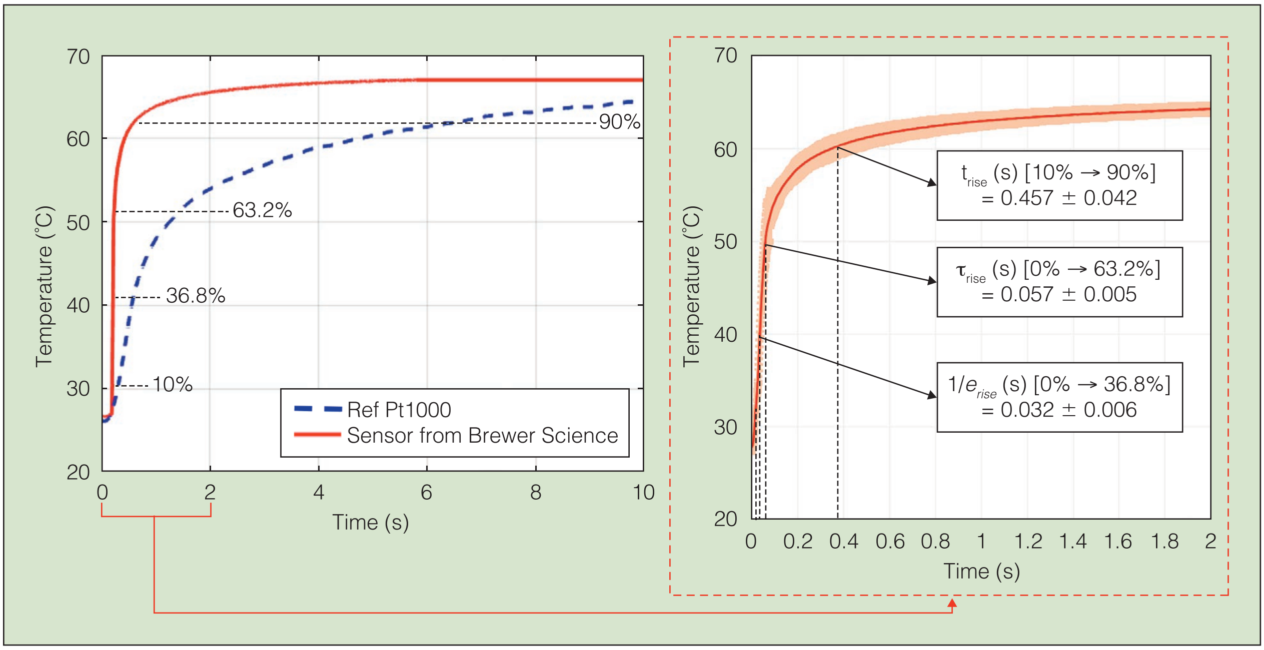

Fig. 3. Comparison between the step response of the old-version Pt1000 (blue dotted line) with the one of the RTD from BS (red solid line).

Table 3 – Comparison of the results obtained with pt1000 and with the RTD from BS.			
	t_{rise}(s)	τ_{rise}(s)	$1/e_{rise}$(s)
RTD Brewer	0.457 ± 0.042	0.057 ± 0.005	0.032 ± 0.006
Pt1000	6.832 ± 0.696	1.663 ± 0.325	0.678 ± 0.143

An average difference of 6.0 ± 1.4% RH could be observed between the values set on the climatic chamber and the RH values measured with the reference sensor from Honeywell (Table 2). Furthermore, comparing the variability of the new sensor with the reference, a strong improvement could be appreciated, in terms of decrease of the standard deviation. The results obtained fitting the experimental measurements showed a good linearity ($R^2 = 0.9948$).

Sensors Dynamic Characterization

The dynamic characterization of the portable sensor system has been performed by evaluating the transient response of the novel sensors to steps of T or H, generated with customized setups (Fig. 2), and comparing their responses with the ones of the previously installed sensors (Pt1000 for T and HYT 271 for RH). The measured values were then processed using Matlab® software, performing an interpolation to get the estimation of parameters variation every 1 ms, and then calculating for every trial with increasing or decreasing steps: the rise/fall time (t_{rise} or t_{fall}), defined as the time to get from the 10% to the 90% of the final value; the response time at 63.2% or time constant (τ_{rise} or τ_{fall}), as the time to reach to 63.2% of the final value; and the response time at 36.8% ($1/e_{rise}$ or $1/e_{fall}$), as the time to reach the 36.8% of the final value.

Temperature sensor dynamic characterization was performed using an oil bath to keep T stable at 63 °C (Fig. 2). After assessing the T stability using a mercury thermometer, the RTD was repeatedly immersed (five times) in the bath, and the transient T values from the room T (26 °C) to the oil T were recorded every 10 ms. The same experiment was repeated for the Pt1000 reference sensor as well, in order to compare the response times. For both sensors, t_{rise} , $\tau\tau_{rise}$ and $1/e_{rise}$ were calculated and compared. The average and standard deviations from the five repetition are summarized in Table 3 and illustrated in Fig. 3.

The results in Table 3 highlight response times for the RTD were more than 10 times faster with respect to the ones of the Pt1000 and also with respect to similar devices presented in the literature [9],[11]. The $1/e_{rise} < 250$ ms declared in the datasheet is largely confirmed from this experimental characterization,

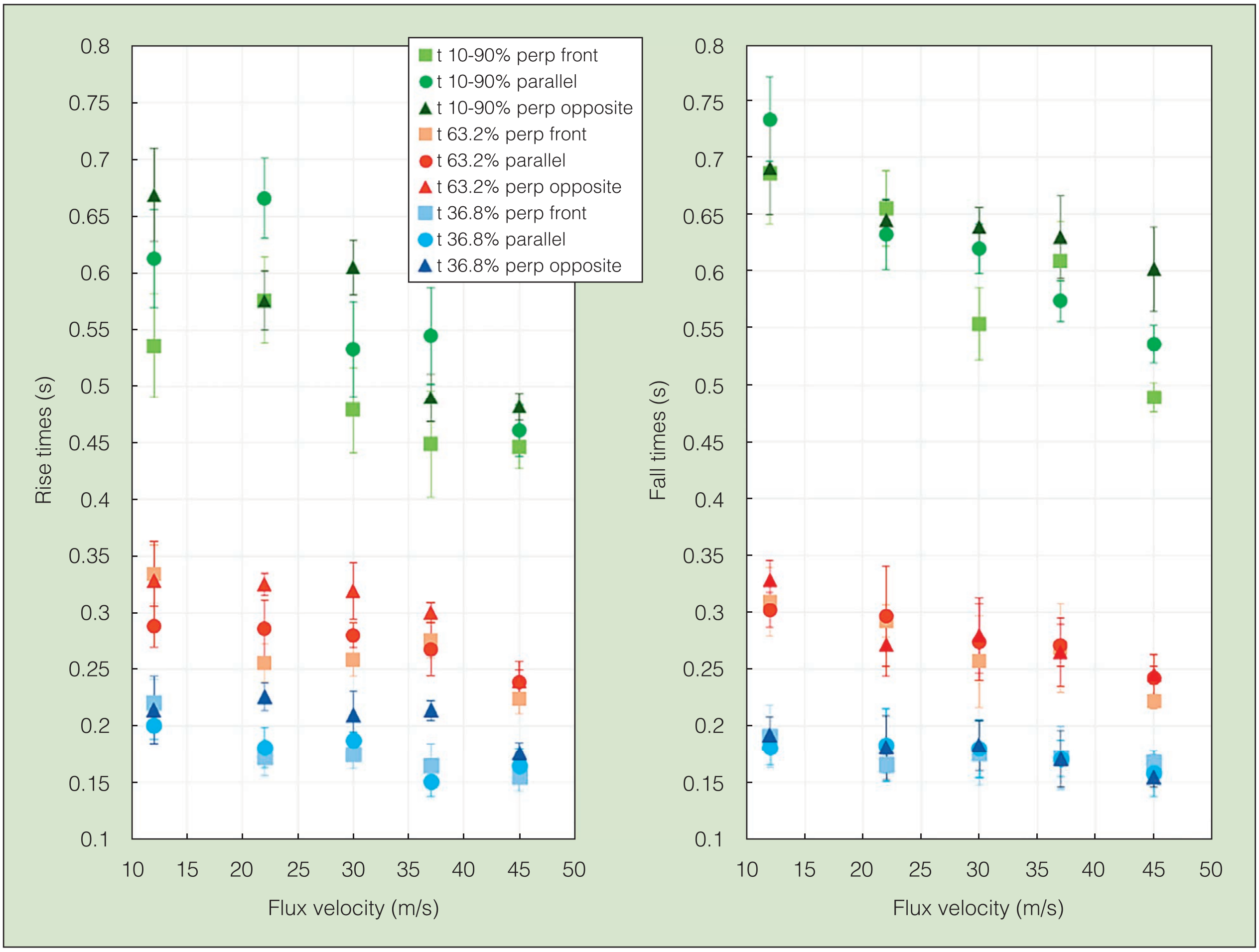

Fig. 4. Comparison between rise and fall response time of the novel resistive H sensor depending on the position and on the air flux velocity.

Table 4 – Comparison of the results obtained with the HYT 271 and with BS sensors.

	t_{rise}(s)	τ_{rise}(s)	$1/e_{rise}$(s)	t_{fall}(s)	τ_{fall}(s)	$1/e_{fall}$(s)
Brewer Sensor	0.446 ± 0.019	0.224 ± 0.013	0.155 ± 0.013	0.489 ± 0.013	0.222 ± 0.007	0.168 ± 0.007
HYT 271	1.056 ± 0.098	0.530 ± 0.007	0.260 ± 0.008	1.736 ± 0.343	0.650 ± 0.088	0.371 ± 0.008

in which the average $1/e_{rise}$ (32 ms) appears suitable to record real time variation during mechanical ventilation.

Humidity sensor dynamic characterization was performed following the same protocol described in [12]. Briefly, using a customized pneumatic system combined with a bubbling humidifier, increasing or decreasing steps of RH between two values of RH were created. Sensors were thus exposed to these RH steps to evaluate their response times. The system, schematized in Fig. 2, is composed of: a compressor (a), which creates a pressure-controlled airflow; a bubbler (b), to increase the humidity; two regulators (VXD232) (c) and (d), that can be alternately switched on or off (opening time around 10 ms) with a customized LabVIEW program, to select the desired path for air flow; reference sensor (e) and Brewer sensor (f) positioned in a tube section at the end of the system with an anemometer TESTO-405-V1 (g) for measuring air flow velocity. If the regulator (d) is opened and the regulator (c) is closed then there is dry air, vice versa the air is humidified. The step obtained by inverting the position of the valves is of around 40% RH. Different flow values from 15 to 45 l/min usually used in MV were analyzed. Furthermore, three orientations of the sensor with respect to the flow direction were chosen to assess sensor response times under the different variable combinations. For each trial, 10 steps were selected, respectively, for the evaluation of both rise (t_{rise}, τ_{rise} e $1/e_{rise}$) and fall (t_{fall}, τ_{fall} e $1/e_{fall}$) times.

In order to provide an explanatory representation of the variation of t_{rise}, τ_{rise} e $1/e_{rise}$ and of the t_{fall}, τ_{fall} e $1/e_{fall}$ depending on the sensor position and on the flux, they are all plotted in Fig. 4.

The values obtained highlight that the fastest response times at 36.8% (155 ms for rising H and 168 ms for falling H) could be obtained by placing the sensor perpendicular in front of the air flux. Results from this condition are summarized in Table 4 and illustrated in Fig. 5, where the responses of

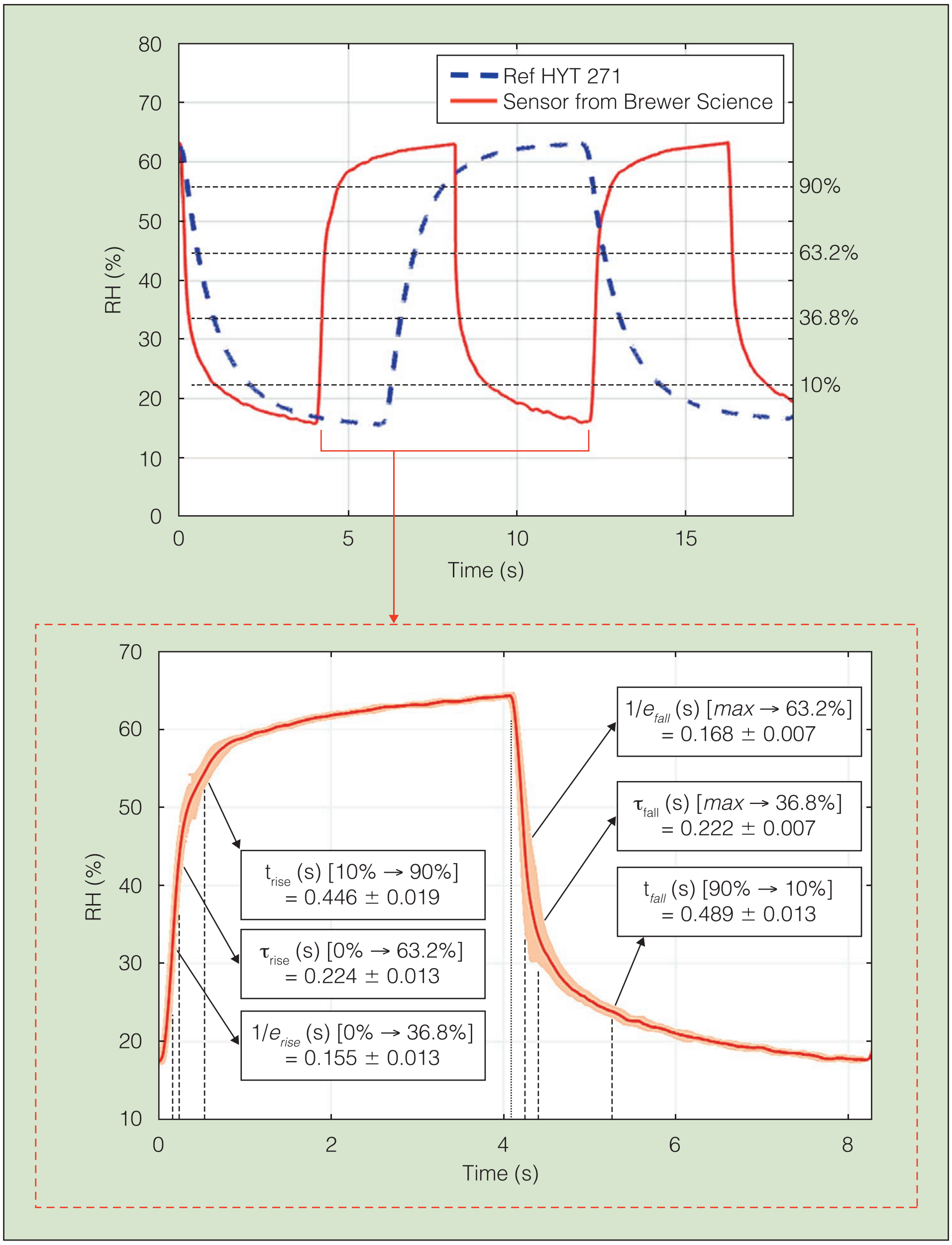

Fig. 5. Comparison between the step response of HYT271 and of BS sensor.

HYT 271 and the ultrafast Hsensor under these conditions are compared, both in terms of response times and then of step response versus time.

Regarding the influence of the air flux velocity, it can be appreciated how sensor response times decreased with the increase of the flow velocity. The higher variability observed in some of the measurements can be addressed to a not perfectly static positioning of the sensor during the test.

With respect to the declared value of 10 ms for $1/e_{rise}$, the fastest response times appeared higher probably due to the delay introduced from the valve opening (around 10 ms). However, considering that in [12] the best t_{rise} and t_{fall} obtained were, respectively, 1 and 1.8 s, the values obtained here with the new H sensor (< 700 ms) appear significantly lower. These values appear also very interesting if compared with the fastest response times obtained from similar devices presented in previous literature: 1.4 s in [10] and 2 s in [11]. Furthermore, comparing the response times obtained during H rise and fall, no significant differences can be observed with the new H sensor, different from what could be highlighted in the use of HYT 271, which appeared slower in its response to decreasing H, thus limiting the possibility to correctly follow inhalation and exhalation phases during fast respiratory rates.

In order to properly assess the range of respiratory rates monitorable using the new sensor, an analysis was performed, similar to what was presented in [12]. Both sensors were modeled as two first order systems [14] using the time constants (τ_{rise} and of τ_{fall} at 63.8%) obtained experimentally with the sensors perpendicular in front of a 45 l/min flux. Using those models [12], it was possible to quantify the percentage of error of the measured H at different respiratory rates.

Results obtained (Fig. 6) highlight how the use of the novel resistive H sensor can reduce the error in detecting the H of almost 5 times compared to HYT 271, allowing the system to monitor respiratory rates up to 35 acts per minute with a maximum error of 5%.

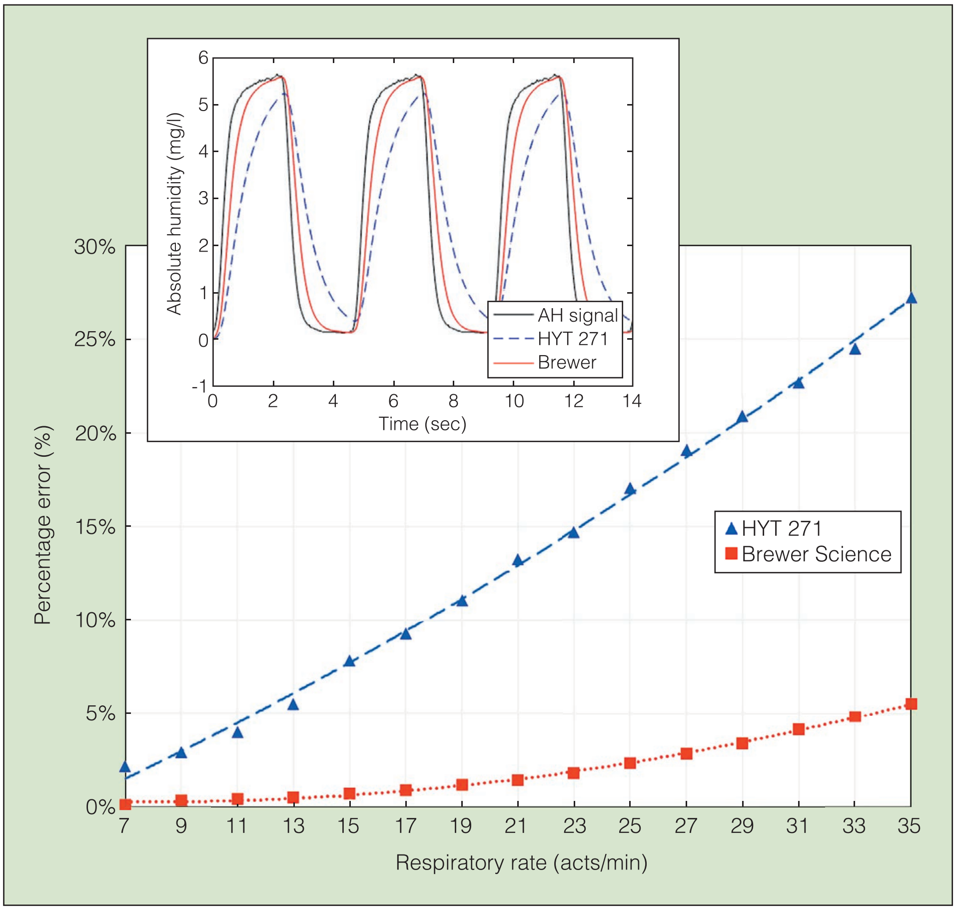

Fig. 6. Comparison between the error of HYT 271 and of H sensor from BS in measuring the maximum value of a typical AH variation during breath, related to the respiratory rate.

Conclusion

An improved measuring portable device has been proposed for real-time monitoring of temperature and humidity during mechanical ventilation. Focusing on the possibility to evaluate HME performances with higher accuracy and shorter response times, an accurate in vitro set up has been designed to test the improvement brought by novel ultrafast humidity and temperature commercial sensors in a portable device compatible with ICU routine. The improved response times (57 ms for T τ_{rise} and around 220 ms for H $\tau_{rise/fall}$) allowed the system to estimate a reduction of almost 5 times of the error in the detection of the proper H value if compared with the previous version of the device. Furthermore, both sensors, due to their reduced dimension, light-weight and flexibility, could be easily integrated and conditioned inside the portable system, without affecting the overall portability and compatibility with the ICU routine. Overall, the integration of the characterized sensors in the portable device allows a real-time and reliable in vivo reconstruction of the T and H of the breath in a wide range of respiratory frequencies, thus making it particularly suitable for HMEs monitoring in clinical environments. Starting from the results obtained here, which confirmed the possibility to improve the accuracy in evaluating HME performance, future developments will integrate the presented device in ICU medical analyses, in order to evaluate also the effect of HME performance on conditioning the air delivered to the patient.

Data Availability

All of the data used to support the findings of this study are available from the corresponding author upon request.

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