Development of Maximal Respiratory Pressures Measurement System at Functional Residual Capacity Level

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***Abstract*—This paper presents a new methodology and system to perform lung function test by measuring maximal inspiratory and expiratory pressures. With this novel system, the maximal inspiratory pressure can be measured at residual volume or at functional residual capacity. Likewise, the maximal expiratory pressure can be measured at total lung capacity or at functional residual capacity. The objective of this project is to develop, test and perform the validation of the new methodology and electromedical system to measure the respiratory pressures with automatic detections of the inhaling and exhaling maneuvers moments, being capable of measuring lung pressures at functional residual capacity. Calibration tests of the flow and pressure sensors were performed to validate the correct function of the electronic system and an experimental procedure was performed in order to assess biological measures. The system has shown steady behavior and the measures acquired are consistent with the literature. Lastly, this system has shown evidence that it is appropriate to measure the inspiratory and expiratory maximal lung pressures at functional residual capacity and, also, at residual volume and total lung capacity, respectively.**

***Keywords*— Functional residual capacity, maximal inspiratory pressure, maximal expiratory pressure, respiratory muscles strength.**

***Resumen*— Este trabajo presenta una nueva metodología y sistema para realizar pruebas de función pulmonar midiendo las presiones inspiratorias y espiratorias máximas. Con este novedoso sistema, la presión inspiratoria máxima puede medirse con el volumen residual o con la capacidad residual funcional. Del mismo modo, la presión espiratoria máxima se puede medir a la capacidad pulmonar total o a la capacidad residual funcional. El objetivo de este proyecto es desarrollar, probar y realizar la validación de la nueva metodología y sistema electromédico para medir las presiones respiratorias con detecciones automáticas de los momentos de maniobras de inhalación y exhalación, siendo capaz de medir las presiones pulmonares a la capacidad residual funcional. Se realizaron pruebas de calibración de los sensores de flujo y presión para validar la función correcta del sistema electrónico y se realizó un procedimiento experimental para evaluar las medidas biológicas. El sistema ha demostrado un comportamiento estable y las medidas adquiridas son consistentes con la literatura. Por último, este sistema ha demostrado que es apropiado medir las presiones inspiratorias y espiratorias máximas del pulmón a la capacidad residual funcional y, también, al volumen residual y la capacidad pulmonar total, respectivamente.**

***Palabras clave*— Capacidad Residual Funcional, Presión Inspiratoria Máxima, Presión Espiratoria Máxima, Fuerza de los Músculos Respiratorios.**

I. Introduction

The strength of respiratory muscles can be measured, directly, by means of the maximal respiratory pressures, which can be determined through the maximal inspiratory pressure (IPmax) and maximal expiratory pressure (EPmax tests [1][2][3]. These tests are volitional and should be performed by an experienced operator, who should instruct and motivate the subject in order to obtain acceptable results. IPmax and EPmax are measured at or close to residual volume (RV) and total lung capacity (TLC), respectively [3][4][5]. A problem with these procedures is that the operator usually does not have access to information about respiratory flow or lung volume, entrusting the responsibility of determining the moment to execute the maneuvers to the subject. When measuring maximal respiratory pressures, another problem arises due to the passive pressures performed by the elasticity of the lung and chest wall. In this regard, at RV and TLC, the respiratory system pressure (RSP) may decrease about $30cmH_2O$ and increase about $40cmH_2O$, respectively. This makes it difficult to

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differentiate between respiratory muscles strength related diseases and pulmonary compliance related diseases [4][5][6][7]. When the lung volume corresponds to the functional residual capacity (FRC) the RSP is null, i.e. the respiratory system is in equilibrium, with no tendency to expand or retract [5][6][7][8].

Monitoring the respiratory flow and volume in real time would make it possible to determine the ideal moment to begin the maneuvers and allow the evaluation of the pressures at FRC. This contributes to the reduction of the viscoelastic properties influence on the measures, facilitating the discrimination between diseases related to respiratory muscle strength and those related to the elastic properties of the respiratory system.

This paper intends to investigate the hypothesis that the evaluation of maximal respiratory pressures could be performed with a device that is capable of automatically determining the moment that the subject should maximally inhale or exhale, allowing the maneuvers to be more easily executed. Besides that, it is expected that the system makes the evaluation of the respiratory muscular function considering the pressures from elastic structures and minimizes the operator-dependent and subject-dependent character. For this, an embedded system was developed, which consists of a hardware, software, and firmware, able to measure the maximal respiratory pressures at Functional Residual Capacity Level, by monitoring respiratory flow and volume.

II. Methods and Materials

The system can be divided in tree main parts, as seen by the highlighted blocks in Fig. 1. The Control Unit is highlighted in blue, the User Interface, in orange and the Sensors, in Green.

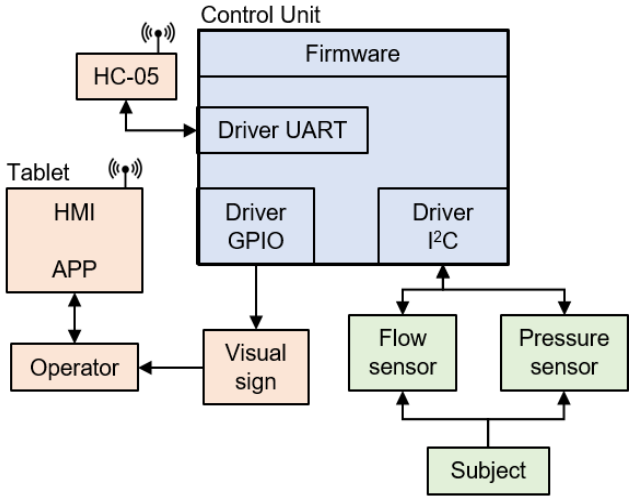

Fig. 1. System block diagram.

A. Control Unit

The control unit consists of a printed circuit board with four layers, which has for the main component the microcontroller STM32F765VIT6 from STMicrocontrollers, from which the following resources were used: one UART module, GPIOs, 2 I^2Cs modules, 2MB of flash memory and 128KB of RAM memory. It also has LEDs for signaling and debugging, connectors that allow communication with I^2C devices, communication by Bluetooth between hardware-interface and USB connector for charging the system battery. It is responsible to communicate with the graphic interface and sensors, perform the required calculus, and determine and indicate when the subjects are at their FRC.

The firmware was developed in the programing language C, in the IDE System Workbench for STM32 and the necessary configurations were made with the STM32CubeMX tool. The flow signal is sampled at 500Hz, and the volume is calculated in real time. Three consecutive and similar breathing patterns must be recognized so the firmware may be able to predict when the subject will be at FRC, therefore being able to activate the visual sign, indicating the moment to initiate the maneuver. The data from the pressure sensor is sampled at 1kHz and transmitted, via UART, to the HC-05, which transmits it, via Bluetooth, to the graphic interface.

B. Sensors

The flow sensor is the SFM3000, a low pressure drop digital flow meter from Sensirion; it is bidirectional, with a flow range of ±200slm and typical accuracy of 1.5%, sample rate up to 2kHz, calibrated, with temperature compensation, zero offset and no drift [9].

The pressure sensor, SSCDRRN005PD2A3, is fully calibrated and temperature compensated for sensor offset, sensitivity, temperature effects, and non-linearity, designed to measure differential pressure into a range of ±5psi [10].

C. User interface

The software used in the graphic interface is the graphic interface MANOVAC 3.0 [1][11]. The pressure samples of the maneuvers are stored and shown graphically in real time at the screen. The following parameters are considered by the software: the maximal respiratory pressure of each maneuver is obtained from the largest mean sustained for 1 second; the largest value of maximal respiratory pressures is select when the measure sequence shows a drop in the maximal respiratory pressures value; and the maximal respiratory pressures value is considered reproducible if the second largest maximal respiratory pressures is at least 90% of the largest, and if the third largest is at least 80% of the largest [1][11].

The visual sign (by a LED) indicates the moment when the operator should indicate that the maneuvers must be initiated. The subject should not be able to see the sign.

D. Calibration

The calibration tests of the flow and volume parameters were made with a three-liter calibration syringe with ±0.5% tolerance (Alpharad, certified with standard and traceable calibration). The flow sensor was connected to the syringe (Fig. 2).

In the first moment, the consistency of the data was analyzed in a serial terminal, five measures of the volume were made with the system being submitted to full excursions of the syringe piston, which pushed a total of 3,000ml of air through the sensor. Five tests were made to evaluate the system error, each one with 15 complete excursions of the syringe piston, being five of them with a flow of 0.5l/s, five with 1.5l/s and five with 2.5l/s. For each one of them a first order approximation was made with the

collected data and a correction factor to diminish the error was calculated.

Fig. 2. Alpharad's calibration syringe.

The calibration tests of the pressure sensor were made with a pneumatic pump, model BY-100/8111-60, and a digital calibrator, model PC-507, both from Presys. The data collected by the system were transmitted to a computer and stored by a graphic interface created with Labview. With the pump and digital calibrator, the following pressure values were inputted: 30, 60, 90, 120, 150, 180, 210, 240, 270, 300 cmH_2O. The system collected data for five seconds at a sample rate of 100Hz, totalizing 500 samples for each pressure value. The acquired data were submitted to a Matlab routine which performed weighted least squares regression to obtain offset and scale correction factors for the system.

E. Experimental Procedure

In order to establish usability of the present work, a pilot study was conducted, in which the maximal respiratory pressure of 6 healthy subjects (5 males), age (years) 25 ± 8.6 (mean ± SD), were assessed. For the IPmax tests, the subjects were seated with feet laying on the ground, and posterior part of the torso supported on the chair. Initially the subjects were instructed to "breath calmly", and, after enough respiratory cycles to the device detection calibration, a yellow luminous sign is turned on indicating to the operator the last cycle before the maneuver. Then, a green visual sign alerts the operator the moment to request a maximal inspiratory effort and, simultaneously, close the occlusion orifice. The subject was then instructed to generate a maximal effort with the verbal command: "Breath out!", with an emphatic and loud tone of voice. The tests were made with a minimum interval, between each measure of one minute, and a maximum of 8 measures [11].

For the EPmax tests the subject was seated, and instructed in the same way as described above. After enough respiratory cycles to the device detection calibration, a yellow luminous sign was activated indicating to the operator the last cycle before the maneuver. Then, another sign, this time green, alerted the operator the moment to request a maximal expiratory effort and, simultaneously, close the occlusion orifice. The subject was then instructed to generate a maximal effort with the verbal command: "Breath in!", with an emphatic and loud tone of voice. During the tests, the operator kept the facial muscles, of the subject, sustained to prevent air accumulation in the lateral region of the oral cavity. The tests were made with a minimum interval, between measures, of one minute, and a maximum of 8 measures [11].

All tests were executed with a nose plug and the subject instructed to keep the diver nozzle tight between the teeth and lips so to prevent air escaping. The ideal duration of the maneuvers was considered to be three seconds and the subjects were oriented to not perform any extenuating physical activities in the 12 hours before the test.

The experimental procedure was performed with 6 subjects (authors of this paper). As the experiment was balanced with paired measures for all pressure measures and the amount of replication are always the same, the data was analyzed by a Two-Way ANOVA, since all the premises (normality, homoscedasticity and independence) were met. The premise tests were the Shapiro-Wilk normality test, Fligner-Killeen test of homogeneity of variances and Durbin-Watson independence test. Lastly, the Tukey HSD test was performed to quantify the difference in the mean measurements of TLC and FRC in EPmax and RV and FRC in IPmax. A significance level of α=0.05 was used for all the statistical tests.

III. Results

The system developed attended to all the project requisites, and is fully operational.

A. System

Fig. 3 shows the electromedical device developed for this project.

The main parts of the system are highlighted in Fig. 3. They are: in green, flow sensor (FS) and pressure sensor (PS); in yellow, Bluetooth module (BT), connector for external LEDs (LEDs) and USB connector (USB); and in red, microcontroller (MPU). The dimensions of the PCB are "54 mm × 86 mm", making the system portable. The battery life in continuous use mode is approximately 8 hours, and can be charged through a USB cable.

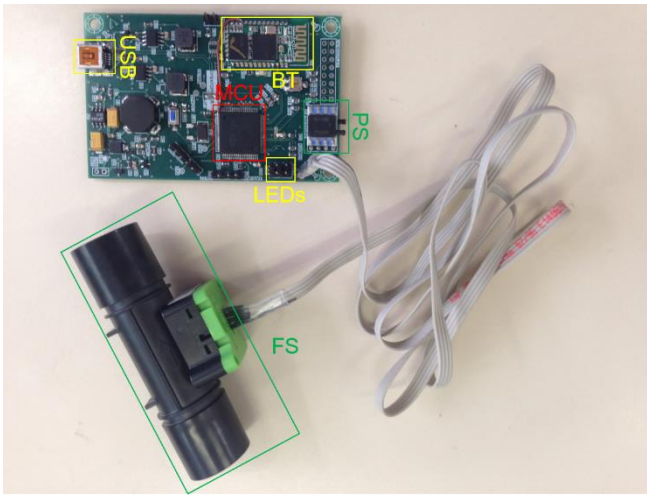

Fig. 3. Electromedical device developed. The main components of the system have been highlighted.

B. Calibration

The system was fully calibrated and showed acceptable error values.

C. *Flow sensor*

The measures made with the serial terminal are shown in Table I. The table presents the error percentage obtained during the calibration of the flow sensor.

TABLE I
VOLUME AND ERROR OBTAINED WITH THE FLOW SENSOR

Mesures	Volume (ml)	Error (%)
Mesure 1	3025.7	- 0.8566
Mesure 2	3000.2	- 0.0066
Mesure 3	2995.0	0.1666
Mesure 4	2980.9	0.6366
Mesure 5	3013.8	- 0.4600

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Fig. 4 presents an example of the flow signal collected by the software during one of the tests with the calibration syringe. It is possible to observe the different excursion velocities of the piston, starting around 0.5l/s, in the first five excursions, and finishing around 2.5l/s in the five last.

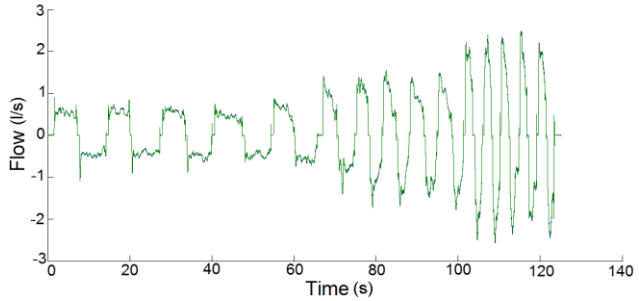

Fig. 4. Flow as a function of time. Graphical representation of the different excursion velocities of the piston used to calibrate the flow sensor.

The correction factors found may be observed at Table II. Table presents the error percentage obtained during the calibration of the flow sensor.

TABLE II
CORRECTION FACTORS OF THE FLOW SENSOR

Test	Injection before (%)	Injection after (%)	Removal before (%)	Removal after (%)	Correction Factor
1	1.1	0.8	0.8	0.4	0.994
2	0.7	0.6	0.6	0.3	0.998
3	0.6	0.5	0.7	0.5	0.998
4	0.9	0.6	0.6	0.4	0.996
5	2.0	2.0	2.4	2.2	0.986

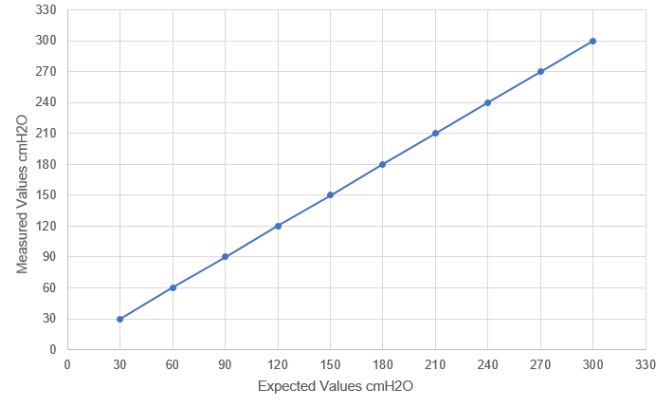

Fig. 5. Calibration curve of the Pressure Sensor.

D. *Pressure Sensor*

The calibration of the pressure sensor showed that the measured values are inside the expected error band. According to [10], there is no need for costumer calibration. The measurement error was inferior to the accuracy of the digital calibrator model PC-507 (0.05cmH_2O). Thus, the measured values were equal to expected values, as can be seen in Fig. 5.

E. *Experimental Procedure*

Table III presents the results of the Two-Way ANOVA performed with the dependent variable IPmax. According to this table, it is possible to notice p-values less than α=0.05, for the factors Procedure, Subject and the interactions between them.

TABLE III
TWO-WAY ANOVA FOR IPMAX

	Df [a]	Sum Sq [b]	Mean Sq [c]	F value	P Value
Procedure	1	1080	1080	32.79	$6.70x10^{-6}$
Subject	5	35506	7101	215.69	$< 2x10^{-16}$
Procedure:Subject	5	1473	295	8.95	$6.63x10^{-5}$
Residuals	24	790	33		

[a]Df = Degrees of Freedom.
[b]Sum Sq = Sum of Squares.
[c]Mean Sq = Mean of Squares.

In Table IV, there are the results of the Turkey HSD Test for IPmax. The difference in the observed means was 10.952 cm$H_2$0, the interval lower end point was 7.004 cm$H_2$0 and the upper end point was 14.899 cm$H_2$0.

TABLE IV
TUKEY HSD TEST FOR IPMAX

	diff [a]	Sum Sq [b]	Mean Sq [c]
RV- FRC	10.95222	7.004714	14.89973

[a]diff = Difference in the observed means.
[b]lwr = Interval Lower End Point.
[c]upr = Interval Upper End Point.

Table V include the results of the Two-Way ANOVA performed for EPmax as the dependent variable. In it, the p-values are less than α=0.05, for the factors Procedure, Subject and the interactions between them.

TABLE V
TWO-WAY ANOVA FOR EPMAX

	Df [a]	Sum Sq [b]	Mean Sq [c]	F value	P Value
Procedure	1	7115	7115	109.212	$6.70x10^{-6}$
Subject	5	35551	7110	109.136	$1.07x10^{-15}$
Procedure:Subject	5	1721	344	5.282	0.00207
Residuals	24	1564	65		

[a]Df = Degrees of Freedom.
[b]Sum Sq = Sum of Squares.
[c]Mean Sq = Mean of Squares.

The Table VI presents the results of the Tukey HSD Test for EPmax, where difference in the observed means was 28.117 cm$H_2$0, and the interval lower and upper end point were 22.564 cm$H_2$0 and 33.670 cm$H_2$0, respectively.

TABLE VI
TUKEY HSD TEST EPMAX

	diff [a]	Sum Sq [b]	Mean Sq [c]
TLC- FRC	28.11722	22.56425	33.6702

[a]diff = Difference in the observed means.
[b]lwr = Interval Lower End Point.
[c]upr = Interval Upper End Point.

IV. DISCUSSION

A. Calibration

The volume data displayed at the serial terminal showed values close to 3000ml with an error of ±1%.

Table 1 shows that the volumetric errors found were less than 2.5%. The biggest values were observed when the system was submitted to bigger flow rates. This was expected, because according to [4], the error is proportional to the measured value. Even in different dynamic conditions the error is maintained below the maximal value of 10% determined by [11].

The correction factors obtained were close to 1, proving that the system is pre-calibrated, and does not need any kind of calibration or adjustment. The measured values were inside the error band of the calibration syringe.

B. Experimental Procedure

According to the Table III of IPmax and Table V of EPmax, the p-value of the dependent variable Procedure was less than α ($p\text{-}value = 6.70\text{x}10^{-6}$, $p\text{-}value = 2.06\text{x}10^{-10}$, respectively), therefore the mean difference is not null between the two procedures. Thus, the measurements produced by both procedures are statistically different for both measures. In [3][6][12][13], it's proposed that the IPmax measures at RV and FRC are different, as observed in this paper experiments. Moreover, the EPmax at TLC and FRC are expected to be different according to [3][6][12][13], which was also observed in this paper.

As expected, the subjects had a statistically significant different measures, due to the inspiratory and expiratory pressures dependence on physiological characteristics of individuals [4][13][14].

The Tukey HSD test for the IPmax, according to Table IV, had as result a means difference of 10.952 cmH20. In the literature, this difference varies depending on the individual, according to physiological characteristics [13][14].

Lastly, the EPmax means difference given by the Tukey HSD test was 28.117 cmH20 (Table VI), which is consistent with the expected value found in the literature according to [13][14].

C. Future Works

It is still necessary to develop a study with the evaluation of more subjects, in order to obtain more reliable statistics of the measures and evaluate the repeatability and reproducibility of the measures.

Also, it is required to validate the application of the new parameter measure on the diagnostics of respiratory system diseases.

V. CONCLUSION

The system has shown evidence that it is able to automatically detect the moment when the subject's lung volume reaches the functional residual capacity, which allows an automatic indication of the correct moment to perform the inhale or exhale maneuvers. This reduces the dependence on the subjective perception of the subjects, and allows the measurement of IPmax and EPmax at functional residual capacity.

The pressure values obtained in the experimental analysis are consistent with the expected values in the literature. Thus, it indicates that the proposed system is adequate for lung function testing at functional residual capacity and, also, at total lung capacity and residual volume.

The measured values at FRC level were statistically different from values measured at RV and TLC levels. This indicates that the new system can be able to measure maximum respiratory pressures in two different ways.

VI. ACKNOWLEDGMENT

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