Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Patented portable spirometer based on fluid mechanics and low energy consumption to monitor rehabilitation of Covid-19 patients

José C. Alvarez*, Carlos Raymundo*, Gianpierre Zapata*, Julio Ronceros*, Marco Floresb, Francisco Ruizb

a Universidad Peruana de Ciencias Aplicadas, Prolongación Primavera 2390, Lima, Lima 33, Peru
b Universidad Nacional Autonoma de Honduras, Bulevar Suyapa, Tegucigalpa, Honduras

Received 1 August 2020; accepted 25 August 2020

Abstract

The evolution of respiratory capacity in convalescent Covid-19 patients must be monitored over time, which is not feasible due to the lack of personal, portable and low cost spirometers that prevent contamination. Here, we propose the design of a portable and personal spirometer, that uses the parabolic movement of a drop of fluid, driven by exhaled air, to measure respiratory capacity. The distance traveled by the drop is correlated with the air and thus, the exhaled air volume. The mechanical design does not require an external energy source and instead relies on the force of the patient’s exhalation. The position of the drop can be measured directly using an interchangeable ruler within the spirometer. The research methodology consists in three stages: idea generation, concept definition (patent), and concept feasibility. In this third stage a simulation with Modellus X.04.05 is realized. We have patented the conceptual design of the spirometer, and additionally present a simulation and feasibility determination of the environmentally friendly and low-cost design. The novelty of this patented spirometer is the use of a simple physical principle to solve a complex problem, without using external energy. Therefore, this artifact can be implemented and widely used in the prevention and control of bronchopulmonary diseases.

© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Peer-review under responsibility of the scientific committee of the Tmrees, EURACA, 2020.

Keywords: Spirometer; Product development process; Fluids mechanical; Mechatronic products; Renewable energies

1. Introduction

Worldwide, researchers and clinicians are studying the pathogenesis of the novel coronavirus pandemic Covid-19, including the possibility of reinfection after illness and recovery [1]. Situations have occurred in which false negative test results have led to patients being prematurely discharged from hospitals, resulting in fatalities. In addition, patients who do experience a relapse often lack access to appropriate post-treatment follow-ups, and may unnecessarily return to the hospital and risk reinfection.

* Corresponding author.
E-mail address: pciijalv@upc.edu.pe (J.C. Alvarez).

https://doi.org/10.1016/j.egyr.2020.08.042
2352-4847/© 2020 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Peer-review under responsibility of the scientific committee of the Tmrees, EURACA, 2020.
It is currently understood that Covid-19 infection in certain vulnerable populations, including older adults and people with obesity or respiratory diseases, leaves patients at a higher risk of severely decreased respiratory capacity, both during infection and after recovery.

Spirometers, which are devices that measure the amount of air that can be held in a person’s lungs and the rate of inhalation and exhalation during breathing, can be used to evaluate a patient’s respiratory capacity. The criteria for measuring a patient’s respiratory characteristics include the forced expiratory volume in 1 s (FEV1), the forced vital capacity (FVC), and the proportion of these two measures, among others [2,3]. In addition, the Borg scale [4] can also be used to measure the level of effort that a patient exerts while using the spirometer, and can therefore determine the effort exerted during exercise or upon feeling shortness of breath. These measures can be used to evaluate a patient’s respiratory function over time, and verify the progressive improvement, or relapse, in functionality after a patient has been discharged.

Patients with COVID-19 often exhibit pulmonary fibrosis and 95% O$_2$ saturation. Patients with an FVC of less than 80% typically have pulmonary fibrosis, which can improve with time. In these patients, the viral infection may still only be a few weeks old, and therefore fixed spirometers cannot be used. Alternatively, portable spirometers may be applied to this population for rehabilitation purposes by tracking patients’ respiratory capacity over time.

The patented spirometer described here uses the physical principle of the parabolic movement of a colored fluid drop. Driven by the respiration force of the patient, the drop’s horizontal displacement reflects the respiration velocity, and thus the exhaled volume.

This device is intended for daily use to assess patients’ evolution during the recovery phase of Covid-19, which will reduce traffic to health centers and therefore the chance of additional infections. The device is intended for many different users, and will provide information about the sequelae in patients’ lung function.

2. Problem analysis

The world is currently experiencing a human health and economic crisis that is unprecedented in the last century and is continually evolving. In the face of the Covid-19 pandemic, economies are closed and paralyzed, and many countries have enacted severe quarantines, measures that are comparable only to those experienced during wartime. Although it is unknown how long the crisis will last or the path the recovery will take, a faster and more forceful response will result in fewer negative effects.

According to the World Health Organization (WHO), “About 1 of each 6 people who get Covid-19 develop a serious illness and have difficulty breathing. Older people and those with underlying medical conditions, such as high blood pressure, heart problems, or diabetes, are more likely to develop serious illness. About 2% of people who have contracted the disease have died. People with fever, cough, and shortness of breath should seek medical attention” Elderly people and people with other medical conditions, such as asthma, diabetes, or heart disease, may be more vulnerable and become seriously ill, causing pneumonia or breathing difficulties.

Within this context, spirometers can provide information of high clinical relevance regarding patients’ respiratory conditions. Spirometers are medical devices that measure a person’s “breaths” (both inhalations and exhalations) by assessing the volumetric flow (Vt), which in a healthy adult person is generally 500 ml. They provide values related to air volume, as well as the flow it generates (time/volume). These tools can be used to detect and evaluate pulmonary dysfunction, and its evolution over time, in rehabilitating Covid-19 patients.

However, because most spirometers are “analog spirometers” are typically used by multiple patients in subsequent consultations, and digital ones are very high cost for people in developing countries, they have the potential to spread the virus.

In this study, we present the development of a novel low cost, portable, and disposable spirometer that can be used by Covid-19 patients who have already been discharged following treatment, thus decongesting hospitals. This low-cost, mobile device is intended to be taken home, used for 15 days to track respiratory progress, and discarded at the end of the process.

3. The working principles of the spirometers

3.1. Differential pressures

Beltrán [5] reported the design and implementation of a portable spirometer that used a measurement method based on a membrane that recorded differential pressures and then transduced those measurements into electrical signals. However, it did not allow for direct measurements using manual or mechanical methods.
3.2. Microturbines

Habibiabad et al. [6] presented the design of a spirometer that used a micro-turbine. When the user breathed out, the turbine would turn and generate a potential difference proportional to the speed of the incoming air flow, allowing the exhaled air flow to be determined. Goreke et al. [7] similarly designed turbines 10 mm in diameter and 1.3 mm thick that featured bearings and ball grooves. These authors found that the optimal turbine design included 11 blades.

Thus, the flow of air blown by the patient passes through a stator that directs the air forming a whirlpool that turns a turbine, whose rotation is associated with the speed of the exhaled air and its volume.

3.3. Venturi effect

The application to US patent US2012/0136271 – SPIROMETER APPARATUS AND METHODS USEFUL IN CONJUNCTION THEREWITH – described a spirometer apparatus made up of three parts: an exhaled air intake duct, an intermediate area for interconnection and measurement, and an outlet duct for the exhaled air, where the exiting air would induce a low pressure region that would direct the air outwards, according to the Venturi principle. This invention made use of the Venturi effect, measuring the pressure of exhaled air passing through a small section with vertical tubes and side holes opposite the exhaled air stream. It featured a very complex design and did not allow for direct mechanical measurement.

The American patent US5137026A PERSONAL SPIROMETER described a self-contained portable spirometer consisting of housing and an air tube with a hole. Inside the cover, a transducer and microprocessor-based circuit would generate a standard measure of exhaled air performance, such as forced expiratory volume (VEF) and peak expiratory flow ratio (PFER). In this patent, the Venturi effect was also used, measuring the differential pressure between the inlet and outlet of a small orifice within the main duct of the spirometer. However, this spirometer could not perform the measurement manually and without electronic components.

Sridevi et al. [8] and Sanchana and Jayanthy [9] presented designs that would detect the exhaled air pressure difference that would pass through a 3D printed Venturi tube, allowing the system to calculate the FVC. The use of 3D printing, which is low cost, would allow this design to be used in many places that could not normally afford spirometers. That meets the evaluation characteristics of lung diseases such as chronic obstructive pulmonary disease (COPD). In addition to measuring FVC, the design would also measure forced expiratory volume in one second (FEV1). In this case, the spirometer could be used to evaluate the characteristics of lung diseases such as COPD; based on the relationship between FVC and FEV1, COPD could be diagnosed.

3.4. Other principles

Sumbul and Yuzer [10] and Eom et al. [11] introduced a system that had the ability to measure and record the movement of the diaphragm using an iMEM-based accelerometer. The shape of the data recorded using the system was similar to the shape of data recorded using an industrial spirometer instrument. Furthermore, it could also be used as a reliable tool in the diagnosis of certain diaphragm-related diseases such as COPD, dyspnea, and pulmonary hypertension, among others.

Molinaro et al. [12] presented a design for a smart textile for respiratory monitoring based on a piezoresistive sensing element. It consisted of a sensor attached to an adjustable elastic strap, which would be placed around the widest part of a patient’s chest. The design was tested in six volunteers, with two trials for each one. The results showed that the device could accurately estimate respiratory rates and showed an average percentage error of approximately 2% compared with a conventional spirometer.

Other spirometers measure the temperature change of a dielectric proportional to the expired air. Some also use ultrasound sensors. Carta et al. [13] presented a spirometer that used differential pressure based on Bernoulli’s principle.
3.5. Low-cost spirometers

Laghrouche et al. [14] proposed a mobile monitoring system that used Bluetooth with low-cost and low-consumption hardware equipment, capable of measuring the flow or volume of gas during a patient’s inhalations and exhalations. The flow measurements were performed with a commercial platinum hot wire anemometer made with MEMS technology. Due to its small size, it had the advantage of not introducing changes in the spatial distribution of the wind. The wireless transmission system also made it possible to record the data acquired on the patient’s mobile phone and then transmit it to the hospital’s processing unit through the GSM network.

Anakal and Sandhya [15] presented the design of a low-cost spirometer capable of storing information in the cloud through a Wi-Fi module, and thus did not require a computer connection (the transmission was carried out using an HTTP protocol). They used a silicon pressure sensor and an ATMEGA328 microcontroller that achieved results with 95% accuracy.

4. Development of methodology for exhaled air flow spirometer

Barbalho and Rozenfeld [16] presented a specific reference model for the development of mechatronic products, which consisted of the following phases: strategy, portfolio, specifications (of each product), project planning, conception (main components and principles of solution), technical design, optimization (detailing and testing solutions for secondary functions), homologation (of the manufacturing process), product validation and certification, market launch, and monitoring of results. The validation of the model in a mechatronic products company determined that there was a greater increase in capacity in the area of “documents and configurations” and was perceived as an improvement of 85% by the respondents. Furthermore, it was also demonstrated that the application of a reference model in PDP could improve the process.

Weidmann et al. [17] studied 55 mechatronic product development models, where mechanical, electronic, and software engineering converge. They established a matrix of 55 rows (one for each model product analyzed) and 17 columns, classified into: discipline (mechanics, electrical engineering, information technology), type of depiction (analytical/numerical/program code, graphical, table/matrix, textual, physical), engineering phase (requirements definition, concept phase, design phase, documentation phase), and type of information (requirements model, functional model, principal model, design model, process, behavioral model). This study provided a basis for models of the development of mechatronic products. Approximately 70% of the product models considered were applied in more than one of the three main disciplines and 33% of the product models were used in all three disciplines. For product models that were used in two of the three main disciplines, the largest overlap was between mechanical engineering and electro-electronic engineering, while the overlap between mechanical engineering and information technology was the lowest. This analysis provided a different picture of the similarities and differences in modeling.

The methodology followed in our work is based on a proposal by Du Preez and Louw [18], where the innovation process begins with a convergent phase consisting of: (i) A stage of idea generation; (ii) A concept definition stage, where the conceptual design is developed and refined; and finally (iii) A concept feasibility stage, where the viability is determined, models and prototypes are developed, and concepts are refined. This work is based on the results and analysis of stages i, ii, and iii; the models and prototypes developed and analyzed here mostly correspond to stage iii.

5. Results

The results are presented according to the stages and phases described by Du Preez and Louw [18], beginning with the convergent phase I.

5.1. Idea generation stage

According to the inventors, one of whom is co-author of this paper, the design idea arose from an original patent for a multi-directional air speed meter based on parabolic motion (Fig. 1). The idea for this original patent came when one of the inventors, while sitting on the edge of a water source, noticed a change in water direction due to a change in the speed of the wind. This effect could be used to measure the speed and direction of air through a
path and point of arrival of water droplets to the inventors, one of whom is co-author of this paper, the idea arises as a patent derived from the original patent of a multi-directional air speed meter through parabolic motion.

During the exhibition of this invention at a contest organized by Instituto Nacional de Defensa de la Competencia y de la Protección de la Propiedad Intelectual (Indecopi), conversations with visitors inspired the application of this device for measuring the speed of exhaled air in a spirometer. Thus, developing the idea for the second patent changed from a flow with three degrees of freedom, to a flow with two degrees of freedom.

At this point it is interesting to note that many patents are naturally derived from a primitive patent, and based on the inventive principles used in the first one. In this way, the technological trajectory of an invention must go through various stages until it reaches the market and/or has the proper social impact.

5.2. Concept definition stage

The UPC patent “expired air flow spirometer” consists of a square section prismatic structure. At one end is a nozzle, where a user can exhale air into the device. This activates a valve that releases a drop of colored liquid, which assumes the speed of the exhaled air and falls a defined distance longitudinally depending on this speed, as shown in Fig. 2, where vessel (1), valve (2), exhaled air nozzle (3), interchangeable recording device (4), prismatic structure (5), vessel support (6):

5.3. Feasibility stage of the concept

A microvalve is activated by the user’s exhaled air, which causes a drop of fluid to fall; the drop then flows with the air and acquires its speed. The “microvalve” works according to Bernoulli’s principle, where pressure differences cause the fluid drop to move downward. This phenomenon has already been used in fuel carburetors to regulate the appropriate air/fuel mixture in internal combustion engines. Bernoulli’s principle is applied at the moment when the air flow passes through the throat of the convergent divergent system, being in this section where the maximum velocity of the fluid occurs and therefore a lower pressure with respect to the pressure where it is located, the liquid tank, thus causing the liquid drops to be immersed in the air flow (see Fig. 3).

Thus, there are two possible variants for actuating the fluid drop. The numerical simulation of the behavior of fluids in both cases was analyzed using the Fluent fluid mechanics computer software, and, to predict the existing interface in a biphasic flow (liquid/air), using the VoF (Volume of Fluid) described by Hirt and Nichols [20]. This method considers that the volume of one phase cannot be occupied by another, giving rise to the concept
of volumetric fraction of phase, where the sum of all the phases will be equal to the total unit. In this way, we will have a general transport equation for multiphasic fluids for a scalar \( \phi \), in the indexical form (shown in Eq. (1)), where the volumetric fraction is represented by the term “\( \chi \)” [21]:

\[
\frac{\partial}{\partial t} (\chi \rho \phi)_m + \frac{\partial}{\partial x_i} (\chi \rho u_i \phi)_m = \frac{\partial}{\partial x_i} \left( \Gamma \phi \frac{\partial \phi}{\partial x_i} \right)_m + \sum_{n=1}^{N_p} c_{\phi, m n} (\phi_n - \phi_m) + \chi (\nabla \phi)_m \tag{1}
\]

Where:
- \( \rho \): density.
- \( u_i \): velocity component in direction \( i \).
- \( \Gamma \phi \): diffusion coefficient for a scalar \( S \phi \): source term for a scalar
- \( N_p \): total number of phases.
- \( c_{\phi, m n} \): mass transfer coefficient between phases \( m \) and \( n \).
- \( \dot{m}_{m n} \): variation of mass per unit of volume, from phase \( m \) to phase \( n \).

To simulate turbulent flow, it will be used the VoF (Volume of Fluid) model and the standard K-epsilon turbulence model [22] were used. ICEM software was used to generate the mesh of the computational domain, using the O’ technique (meshing of the control volume in the form of O) and taking into account the refinement in the walls of the domain, for viscous effects. The meshing is shown in Fig. 4.

5.4. Simulation of spirometer with modellus X.04.05

The drop, when falling, will have traveled horizontally on a graduated line. Small spheres of adsorbent material would be placed at distances along this line. When the liquid drop falls and contacts the corresponding sphere, it will
cause an increase in the volume of the adsorbent material. This design describes a portable mechanical spirometer that only uses a patient’s energy for the evaluation of their respiratory air velocity.

Expiration varies according to the age and gender of a person. For a healthy person, the range of air flow in a forced expiration, during the first second, has a maximum of 12 liters per second and the peak flow during normal breathing is less than 0.5 l per second. That is why, from the measurement with a spirometer, of the forced expiration by a person who has suffered from COVID-19 disease, we can visualize their lung damage.

The use of software for modeling physical phenomena is a great tool for simulating behavior. Modellus X.04.05 was used to simulate the operation of the spirometer. The design of the spirometer, the dimensions of the chamber (parallelepiped), the diameter of the drop, the viscosity coefficient of the air, the density of the fluid, and the movement of the drop were considered when mathematically describing the spirometer (see Fig. 5).

In order to model the behavior of a particle in Modellus, the equations of motion in two dimensions were used. For the simulation, the air viscosity, fluid density, and drop diameter were considered. The parabolic behavior of the drop was restricted by the indicated parameters, as failure to consider them would affect the results (e.g. The maximum range of the drop).

The drop exhibits parabolic motion, as the drop is initially in free fall in one dimension (vertical) and is then affected by the velocity of the exhaled air (horizontal). The equations of motion were separated in the two dimensions throughout the trajectory.

\[
y(t) = h - \frac{g(e^{-\alpha t} + \alpha t - 1)}{\alpha^2}
\]  

(2)
\[ x(t) = \frac{v_0}{\alpha} \left( 1 - e^{-\alpha t} \right) \]  

(3)

\[ \alpha = \frac{18\eta}{\rho d^2} \]  

(4)

Considerations:

- Air viscosity: \( \eta = 1.85 \times 10^{-5} \text{ N m}^{-2} \text{s} \)
- Density of water: \( \rho = 1000 \text{ kg m}^{-3} \)
- Drop diameter: \( d = 1 \text{ mm} \)
- Gravitational acceleration: \( g = 9.8 \text{ m s}^{-2} \)
- Quantity that relates the air viscosity, fluid density and drop diameter: \( \alpha \)

Area of the nozzle: \( 0.000314 \text{ m}^2 \) (10 mm of radius)

In the simulation carried out in Modellus, we could vary the flow rate of the blow and thus modify the parabolic behavior of the droplet, particularly the horizontal range that we were interested in determining.

The simulation carried out in Modellus shows the behavior of the movement of the droplet when the velocity of the blow caused by the entrance hole varies. This simulation indicates the values of the maximum range of the drop that can be obtained when carrying out the experiment and comparing if the model used is the appropriate one.

5.5. Feasibility stage of the electrical and software concept

The increased volume of the adsorbent material would lead to the activation of a digital circuit indicating the horizontal position reached by the drop. This distance is a function of the air speed and therefore of the volumetric flow of the exhaled air. This was considered in claim 7 of our patent, which said: “An exhaled air spirometer according to claim 1, wherein the removable and interchangeable recording device (4) comprises a sensor that will send a signal to a transducer, which will convert it into an electric signal and then send it to a microprocessor and then to a display.”

Thus, the device will be connected to an App that is connected to an internet server, where the doctor can access the results.

6. Discussion

6.1. Results analysis

Here we describe a method for measuring the velocity of exhaled air based on the parabolic movement of a fluid drop and its horizontal displacement in the exhalation direction, as is claimed in our US20180245954A1 patent [19].

The release of the fluid drop is regulated by a microvalve, which operates according to Bernoulli’s principle and uses the exhaled air as an energy source.

The operation of the spirometer was simulated in Modellus X.04.05 for three volumetric flows, determining the horizontal distance traveled by the drop of fluid.

6.2. Future work

In our future work, the spirometer will be connected to a digital network that can store data in a digital cloud for monitoring and subsequent diagnosis. This device is intended for patients who have been discharged and require rehabilitation treatment at home for periods of approximately 15 to 30 days with the supervision of a doctor specializing in pneumology.

The electronic component of the design will allow the data collected over the course of rehabilitation to be accessed using a mobile application and saved to a cloud network with private storage. The object of the project is to produce a functional prototype that will be integrated into the sensors and the network. The information collected in this project will improve future diagnosis, as well as the pulmonary rehabilitation of COVID-19 patients who have been discharged but require monitoring of their rehabilitation at home.
Further, a system will be developed for remote monitoring and diagnosis of COVID-19 rehabilitation patients, which will use artificial intelligence and data analytics. These techniques will provide better diagnostic tools and anticipate health strategies for medical treatment.

7. Conclusions

Inspired by CONCYTEC’s financing of research projects related to COVID-19, we describe the translation of a conceptual design for a spirometer into a detailed design, prototype, simulation, and patent. This distinct design is more advantageous than other spirometers described in the literature due to its low-cost and manual functionality.

This product presents differences and advantages respect others spirometers existing in the literature.

In the idea stage generation is important the originality and the creativity to have it, in this case it arose spontaneously when one of the inventors was close to a water source and the wind moved a part of water.

In the concept definition stage, the parabolic movement is applied to a drop of colored liquid that is coupled to the displacement of the expired air flow and its distance traveled as a function of its speed and volume.

In the feasibility stage of the concept, details are defined such as the valve for the activation of the drop of the colorful liquid, the sensors at the arrival of the fluid, simulations are performed, and the links are established through sensors with the cloud through the cell phone use.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors acknowledge the support from the Consejo Nacional de Ciencia, Tecnología e Innovación - Concytec, Perú, through “Special Projects: Response to COVID-19” (043-2020).

References

[1] Law SK, Leung AWN, Xu C. Is reinfection possible after recovery from COVID-19? Hong Kong Med J 2020;26(3):264–5. http://dx.doi.org/10.12809/hkmj208601.
[2] Higashijima M, Shiozu H, Ueda T, Kurozumi C. Utility of a simple expiratory pressure measurement device in the evaluation of pulmonary function. Int J Gerontol 2018;12(3):208–11. http://dx.doi.org/10.1016/j.jige.2018.03.010.
[3] Mathivadani, Preetha S, Priya J. Evaluation of pulmonary function testing on information technology professionals. Drug Invent Today 2018;10(11):2241–3.
[4] Segura MNH, Cortés HR, Menez DD, Espinosa LFD, Sosa EE, Torres SBA. Correlation between borg’s scale and spirometer in asthmatic patients. Rev Alergia México 2005;52(3):127–31.
[5] Beltrán O. Diseño e implementación de un espirometro Tekhné. 2013 2013;10(2):5–14.
[6] Habibiabad S, Dogrusoz YZ, Beyaz MI. Characterization and performance estimation of a MEMS spirometer. Procedia Eng 2016;168.
[7] Görcke U. Habibiabad S, Azgin K, Serimagaoğlu Y, Ilker M. The development and performance characterization of turbine prototypes for a MEMS spirometer. IEE Sensor J 2016;16(3).
[8] Srivehi P, Kundu P, Islam T, Shahnaz C, Fattah SA. 2019. A Low-cost venturi tube spirometer for the diagnosis of COPD. In: IEEE Region 10 Annual International Conference, Proceedings/TENCON, 2018-October, art. (8650092) pp. 723-726.
[9] Sanchana B, Jayanthi AK. Design and development of spirometer using labview. J Int Pharmaceut Res 2019;46(4):65–8.
[10] Sumbul H, Yuzer AH. Measuring of diaphragm movements by using iMEMS acceleration sensor. In: ELECO 2015-9th international conference on electrical and electronics engineering, art. (7394532), 2016, pp. 166-170.
[11] Eom J, Kim B, Kim W, Lee S. Evaluation of material decomposition for pulmonary function test in spectral computed tomography: A Monte Carlo simulation study. Optik 2018;174:409–15.
[12] Molinaro N, Massaroni C, Presti DL, Saccomandi P, Di Tomasso G, Zollo L, Peregó P, Andreoni G, Schena E. Wearable textile based on silver plated knitted sensor for respiratory rate monitoring. In: Proceedings of the annual international conference of the IEEE engineering in medicine and biology society, EMBS, 2018-July, 2018, art. (8512958) pp. 2865-2868.
[13] Carta R, Turgis D, Hermans B, Jourand P, Oncin R, Puers R. A differential pressure approach to spirometry. In: Biomedical circuits and systems conference, BIOCAS, 2007.
[14] Laghrouche M, Sadaaou R, Mellal I, Nachef M, Ameur S. Low-cost embedded spirometer based on commercial micro machined platinum thin film. Procedia Eng 2016;168:1681–4.
[15] Anakal S, Sandhya P. Low-cost IoT based spirometer device with silicon pressure sensor. Adv Intell Syst Comput 2020;1118:153–61.
[16] Barbalho S, Rozenfeld H. Modelo de referência para o processo de desenvolvimento de produtos mecatrônicos (MRM): validação e resultados de uso. Gest Prod 2013;20(1):162–79.
[17] Weidmann D, Isenmann M, Kandlbinder P, Hollauer C, Kattner N, Becerril L, Lindemann U. Product models in mechatronic design. In: Proceedings of PICMET ’17: Technology Management for Interconnected World, Portland. International Center for Management of Engineering and Technology; 2017.

[18] Du Preez N, Louw L. A framework for management the innovation process Portland international conference - PICMET 2008, 2008.

[19] Alvarez J, Palomo Alvarez A. Instrument for measuring air speed by means of parabolic movement and measuring method. 2018, US Patent. US20180245954A1.

[20] Hirt CW, Nichols BD. Volume of fluid (VOF) method for the dynamics of free boundaries. J Comput Phys 1981;39:201–25.

[21] Rivas JR. Modelo Matemático e Simulação Numérica da Atomização de Líquidos em Injetores Centrífugos de Uso Aeroespacial. (Ph.D. thesis), Area of Propulsion and Energy - Instituto Tecnológico de Aeronáutica, São José Dos Campos – SP - Brazil; 2015.

[22] Lauder BE, Spalding DB. The numerical computation of turbulent flows. Comput Methods Appl Mech Engrg 1974;3(2):269–89.