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The physics of the lungs, a review from the point of view of physics didactics.

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Abstract

Background and objectives: *This review article presents, in an intelligible way, some physical aspects linked to the respiratory system, with emphasis on the lungs, explaining them from the scientific epistemology, making use of physics and the physiology of respiration. The aim of the enquiry is to know some fundamentals of physics that explain the behaviour of the lungs in human beings.*

Methods: *With a descriptive and analytical approach, were examined 57 references in six search engines, selected for their academic and quality explanation. The information search procedure used finders boolean search engines.*

Results: *Exploration of the physical functioning of the lungs; mechanical properties of the lungs, dynamic properties of the lungs; critical physical variables and the thermodynamics of the lungs.*

Conclusions: *Because of this review, we understand how physics relates to the respiratory system from an explanatory perspective. Thus, it encourages reflection on the care and preservation of the lungs, which may eventually be of interest to physicists and non-physicists alike.*

Keywords: *lungs, physics, properties, functioning of the respiratory system.*

Introduction

It has been 1459 years since the publication of *Christianismi Restitutio* by Miguel Servert who was considered the first scientist to understand the mechanism of respiration [1]. Breathing is a process that could not occur without the help of, among other organs, the lungs. The lungs are the focus of the respiratory system, a pair of cone-shaped organs. They are housed in the chest cavity. When we inhale air, it enters the lungs and the oxygen (O_2) contained in the air circulates into the blood. Simultaneously, carbon dioxide (CO_2), a waste gas, is released from the blood into the lungs and exhaled [2].

Thus, knowledge and understanding of how the lungs work is the product of contributions from disciplines such as physics, chemistry, biochemistry, technology, and of course, medicine, which together have enabled everything from the monitoring of lung health to the design of biomedical devices for lung function.

In this regard, the importance of understanding how these vital organs work continues to be a relevant academic activity. Since it has allowed the design and improvement of sophisticated devices that perform a life support function; thus, when a person is in critical condition or undergoes complex surgeries, such as transplants, or cardiac revascularisation, it is the extracorporeal membrane oxygenation (ECMO) equipment that increases the chances of survival [3,4]. ECMO is able to perform the function of the lungs because it oxygenates and ventilates the blood flow [5].

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The EMCO is undoubtedly the result not only of human ingenuity but also of the materialisation of scientific disciplines such as physics, engineering and technology. Without a doubt, the key factor for its proper use is training, as it is a device whose operation is due to its components (Venous drainage and arterial return catheters; Monitoring system of haemoglobin saturation of the drained blood; Suction pressure monitoring; Thermal regulation system; Centrifugal pump; Heparin pre membrane infusion systems and connection of intercalated extra renal clearance devices; Oxygenator; Transmembrane pressure monitoring; Arterial return with its pressure control) requires high specialisation [3,6].

Because lung function is subject to physical principles, it is important to understand some physical concepts and their link to the lungs. Eventually, some scientifically literate people understand the effect of altitude on blood oxygenation and respiratory rate [7]; however, there are other physical phenomena present in the lungs that are relevant to understand, first from a predictive point of view, e.g. hearing wheezing (high-pitched sounds) when breathing is an indicator that the airways are blocked [8]. Then, to make quick decisions, as low levels of oxygenation (hypoxia) can lead to cerebral or pulmonary oedema and even death [7].

Also, in the process of this enquiry, this research team became aware of the imprecise use of terminology in physics, for example, in some articles [9, 10, 11; 12; 13] refer to the definition of resistance as Ohm's Law, when this law actually relates a proportionality of current density and electric field [14, 15]. This conceptual imprecision is considered to lead to incorrect interpretations from a physical point of view.

Thus, the aim of this descriptive review article is to know some fundamentals of physics that explain the behaviour of the lungs in humans. Therefore, these vital organs, lungs, are analysed from a physical point of view, articulated with a brief physiological explanation, which is no less relevant, since its scrutiny would exceed the objective of this review article.

1. Methodology

The following stages of elaboration were followed for this paper, suggested by Ramírez [16], first, a search for information was carried out in the following search engines: Google Scholar, Scopus, Medline, Compedex and Embase; from which 25 review articles were analysed. The keywords were: lungs, physics, properties, and functioning of the respiratory system, these words were combined and finders boolean OR and AND were used in search engines. After the shared reading and socialisation of the content among the authors of this document, were defined the selection criteria for the 56 references. These criteria are based on the following characteristics: relevance to the subject matter addressed in this work; the exposition of the content; the authority of the author of the document; the level of specialisation and accessibility.

Likewise, five books on theoretical university physics; two books on physical chemistry; five books on medical physiology and the respiratory system were consulted; the rest of the documents were located on university websites, repositories of postgraduate theses, laboratories and research institutes, for the analysis of the information. Similarly, were consulted medical libraries for analysis and explanation of the physical principles related to respiratory physiology. Finally, based on the reading and qualitative route mapping of the information, some sections were included, which will be presented throughout the document, as it is true that this review is superficial, because it does not cover the entire spectrum of physical phenomena that take place in the lungs.

Thus, some characteristics will be analysed, such as, the physical functioning of the lungs; mechanical properties of the lungs; dynamic properties of the lungs; critical physical variables and the

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thermodynamics of the lungs. The paper closes with some reflections on risk factors and the cost of breathing if lung function were to fail, and finally some conclusions.

2. Physical functioning of the lungs

When we breathe, the air we inhale describes a movement that oscillates from a region of higher to lower pressure, as this is the native movement of gases [17]. Thus, the exchange of oxygen and carbon dioxide (see figure 1), as previously mentioned, is possible due to the pressure difference between the inside of the lung and that exerted by an external force. Under normal conditions, inspiration occurs when the alveolar pressure drops below atmospheric pressure, i.e. a negative pressure [18].

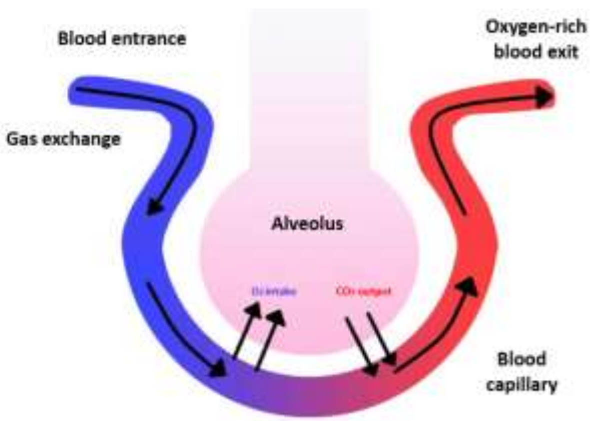

Fig 1. View of gas exchange. Source: Own elaboration.

Then, according to [18] during the movement of the diaphragm (parachute-like muscle separating the chest cavity from the abdominal cavity) and chest walls due to the intercostal muscles, force is produced to achieve the aforementioned negative pressure, encountering resistance to air movement by the presence of elastic resistance of the lung walls and, by the frictional force against the airflow in the lung, chest wall tissue and airways [19].

In this sense, a relevant concept in the functioning of the respiratory system is conservative work, since work is defined by forces. It specified that a conservative force is any force for which the work it does in a closed trajectory is zero [20]. This is equivalent to stating that a conservative force does the same amount of work in going from a point A to a point B ($W_{P \to Q}$), regardless of the path or route chosen (see figure 2). That is, the work done will be the same if a shorter, steeper, or longer route or a flat route is taken [20].

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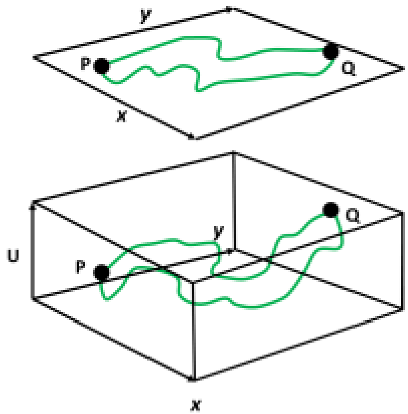

Fig 2. Trajectory for conservative forces. Source: Own elaboration.

On the other hand, if the total work done by a force, operating on a particle as it moves around a closed trajectory and returns to its starting point, is zero, then it is a conservative force, but if the total force of the round trip is not zero, then it is a non-conservative force. Expressed in another way, this implies that, if work is known $W_{P\to Q} = -W_{Q\to P}$ is known; therefore$W_{Q\to P} + W_{P\to Q} = 0$.

In this tenor, the work required to overcome friction (non-conservative force, it does non-zero distinct work in a closed path) is lost, but the work done to contain the elastic resistance of the chest wall is conserved, and used in the spring-like expiration process, as the spring, it turns out, is an example of a conservative force [14]. Thus, when a force exerted on the spring to stretch or compress it, there is an initial displacement at the end, according to Hooke's Law [21].

3.1 The mechanical properties of the lungs

For physicians, understanding the viscoelastic properties of respiratory mechanics has made it possible to represent the behaviour of the respiratory system through a model, which, when anomalies are present, are predictors of problems in the respiratory process [22]. From a physical point of view, these variables constitute properties that are associated with and explain certain physical phenomena. These viscoelastic properties are described below elasticity, viscosity, surface tension and hysteresis.

Elasticity. Defined as the ability of the lungs to expand, due to elastin and collagen [23]. Now, this singular manifestation of the naturalness of force, according to the central principles of Leibnizian dynamics, is elasticity, which from a physical point of view is a mechanical property that allows a body to return to its primitive form after the forces that cause the body to stretch cease [24]. Although bodies with this property, when exceeding the elastic limit, cannot recover their original shape, this does not occur with lungs, as they inflate and deflate thanks to elastic tissues and do not lose their shape [25]. The above, if the lungs have not been affected due to a previous disease that causes to not be able them to expand fully [8].

Viscosity. A term suitable for liquids, it is the analogue of friction in solids, where it manifests due to forces parallel to the surfaces of contacting objects whose direction opposes movement [20], lung viscosity refers to friction within the lung tissue, this friction is necessary to perceive the movement of air in the lungs [26].

Surface tension. Defined as a property of the surface of a liquid that allows it to withstand an external force, its units in the international system are N/m [27]. For the lungs it represents a relevant resistive

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element, which is created at the gas-liquid interface of the alveolus (small pockets inside the lungs, where the oxygen-carbon dioxide exchange takes place, between the lung and the blood), so when we inflate the lung, the surface tension also increases as the volume increases [28].

According to [29], surface tension in an air-liquid contact region induces forces that tend to decrease the surface area of the contact area. Thus, the pressure of a gas inside a bubble is greater than the pressure of the surrounding gas, since the bubble surface is in a state of tension. Then, since the alveoli emulate bubbles in this case, in this condition, it is possible to determine the pressure in the alveoli (bubbles), which is greater than the pressure surrounding it, in a proportion that depends on the surface tension of the liquid and the radius of curvature of the alveolus, according to the Laplace equation [30]:

$$P = \frac{2T}{R} \tag{1}$$

Where, P is the pressure inside the alveolus (Pa). The calculation of this pressure is key to avoid the collapse of the alveolus [31], our lungs have approximately 150 million of these [2] (National Heart, Lung, and Blood Institute, 2022); T is the surface tension of the fluid (N/m) y R is the radius of the alveolus (m). Therefore, the smaller the alveolar radius, the higher the pressure [32].

Hysteresis. From a physical point of view, hysteresis is the predisposition of a material to conserve one of its properties in the absence of the stimulus that provoked it [33]. Thus, according to Serra (2010), the hysteresis of the respiratory system, which is the behaviour during the filling and emptying of air, can be analysed by means of the static pressure-volume curve. This curve is a graphic model, a valid instrument for the study of the mechanical properties of this system [34]. Thus, the static pressure-volume curve constitutes a satisfactory means of adjusting mechanical ventilation to minimise lung stress when a patient subjected to mechanical ventilation [34].

3.2 Dynamic properties of the lungs

Returning to what was mentioned in the section on the physical functioning of the lungs, the force required to balance and overcome air resistance in the lungs is a dynamic process that is affected by the airflow velocity, a velocity that depends on the pressure difference and the resistance to gas (air) flow. Thus, for a better understanding, we resort to the analogy proposed in [14], where air, being a fluid, behaves like an electric current and then it can be analysed with the definition of resistance which relates that: the potential difference applied to a conductor between the current passing through it, is expressed according to equation 2 [14]:

$$R = \frac{\Delta V}{I} \tag{2}$$

Where, R is the resistance of the conductor (Ω) ; ΔV is the potential difference e I is the current, the flow of charge through the conductor per unit time, (A).

Thus, the electrical analogy with airflow considers resistance to air flow as equivalent to electrical resistance (assuming laminar flow). (Ω) (assuming laminar flow). The air flow corresponding to the electric current $(A)$the air pressure difference equated with the potential difference (ΔV) and, finally, Poiseuille's law corresponding to the definition of resistance. This is due to the law of conservation of charge, which forces all charges entering a junction to leave it [14], see figure 3.

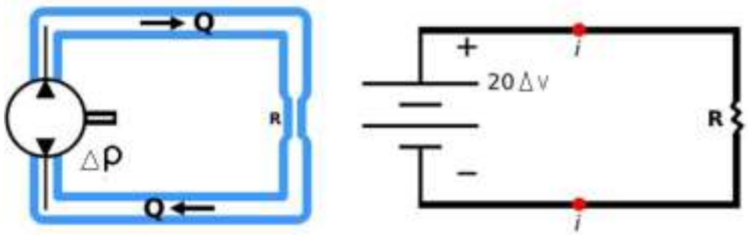

Fig 3. Analogy of a hydraulic circuit and an electrical circuit. Source: Own elaboration.

The flow of air through the alveoli, analogous to a pipe, follows the same principles of analysis for liquids, i.e. the diameter of the airways is the key variable that determines the resistance to air movement, for its understanding it is analysed with Poiseuille's law, according to [30]. Poiseuille was interested in understanding how blood circulated through the capillary vessels in the human body. Sometime later, Hagen, through an experiment, discovered this relationship, materialised in the following Hagen-Poiseuille equation [35]:

$$Q = \pi \frac{\Delta P R^4}{8 \eta L}$$

(3)

Where, Q is the air flow rate (m^3/s); , ΔP is the pressure difference (Pa); , R is the radius (m); , η is the viscosity $(Poise = kg/m\,s)$; / y L is the driving length (m).

This law helps to understand how the variables associated with Poiseuille's equation influence the pressure loss only at the radius where a small decrease would cause a significant increase in pressure, implying that a reduction in the airway compromises the functioning of the respiratory system. It is concluded that there is a directly proportional relationship with the length of conduction; it is also proportional to the absolute viscosity of the flow analysed [29].

Thus, factors affecting lung function include the number of airways, their cross-section, the length of the airways, these factors in turn depend on age, size, lung volume, airway geometry, viscosity and density [36].

3.3 Key lung pressure, flow and volume variables

Fritz Rhorer, in agreement with [37], noted that pressure, flow and volume are key variables in characterising the mechanical properties of the lungs; they also share common physical variables relevant to hydrodynamics. Use returning to the relevance to the lungs, measurements of airflow and lung volume to distinguish lung disease types and severity [38].

In fact, airflow is a key concept in any ventilation system. In thermodynamics, the branch of physics that studies energy transformations [39], the part of the universe that is the object of study is called the system and the part that can interact with it is called the environment [40]. The scientific premise that accredits this relevance is the higher the airflow, the higher the air renewal in closed systems (see Table 1).

In the case of human lungs, when little air enters the lungs, walking is very strenuous; because it involves increased exertion, it is a symptom of obstructive lung disease, which is usually progressive and eventually leads to death [41].

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Table 1. Type of thermodynamic systems

System	Open	Closed	Isolated
Concept	There is a transfer of matter and energy with the environment.	There is no transfer of matter, but it is possible to transfer energy with the environment.	It is a closed system, but where there is no transfer in any way with the environment.

Note. Adapted from *Physical Chemistry*, [41].

Volume, a derived quantity associated with the fundamental quantity length, from a physical point of view is the space occupied by a body [42]. It is a concept that is implicit in other physical variables, such as density and expenditure. Lung volume is quantified in terms of the amount of air that enters and leaves the lungs or remains in them; this quantification can be carried out using an instrument called a spirometer [43]. The spirometer is the product of the inventiveness of the English physician John Hutchinson, who, in 1890, after a series of experiments managed to design a calibrated bell sealed with water, which managed to store the volume of air exhaled after a maximum inspiration [44, 45]. It is pertinent to mention that lung function measurement is a predictive metric of survival [37].

Therefore, lung volume is a specific product of the mechanical and static properties of lung tissue, rib cage and airways [46]. According to [47], the main volumes and capacities to be monitored in humans are tidal volume (VT); inspiratory reserve volume (IRV); expiratory reserve volume (ERV); inspiratory vital capacity (IVC); residual volume (RV); inspiratory capacity (IC); functional residual capacity (FRC); total lung capacity (TLC). Therefore, when some of the reference values, for volumes and capacities, go out of range, they are warning indicators for physicians. For its part, the variable pressure (force per unit area that blood exerts on the pulmonary arteries) in high ranges can block or destroy the blood vessels of the lungs. In fact, the lung and the rib cage remain in intimate and interdependent contact due to negative pressure [48], a negative pressure is a pressure lower than atmospheric pressure [49].

In physics, pressure is a derived quantity that quantifies the force exerted per unit area [15]. This variable, at an industrial level, is responsible for maintaining the quality of a product, since changes in pressure affect production processes. In the field of safety, it is linked to pressurised containers, which must not exceed the maximum value established by the design specifications [50]. For humans, then, blood pressure is key to reducing morbidity and mortality from cardiovascular disease and cardiopulmonary complications [51].

3.4 Thermodynamics of the lungs. Work and Entropy

On the other hand, if we look at the lungs from another branch of physics, we find that thermodynamics explains the behaviour of the pulmonary system, involving two relevant and interrelated concepts: work and entropy. Work is a scalar physical quantity. According to [15], work is done on an object when the point of application of the force moves along a displacement. In the international system, the units are measured in Joules. (J). From a physical point of view, work is the transfer of energy by means of a force, which is why, when we inhale and exhale, i.e. the lungs inflate and deflate, they do work and the use of energy is low; entropy then measures the energy that we do not use and remains in reserve in the body. This is possible because classical entropy allows us to measure the level of work loss in the lung due to irreversibilities in the gas exchange process [29].

In this sense, from a thermodynamic point of view, the human body is an open system [52], because when we breathe we also release energy, manifested as heat and work. It is clear that energy is present in all physical processes, since energy in a system measures the capacity to do work.

3.5 The risks of breathing

Our cells require oxygen for organs to perform their functions [15] note that approximately $5\,kcal$ energy is expended for every litre of oxygen consumed. This means that a healthy adult breathes in $7\ a\ 8\ L$ of air (oxygen content) per minute [41]. However, there are genetic lung diseases, such as cystic fibrosis [53] and others such as silicosis, berylliosis, siderosis, asbestosis, and pneumoconiosis, among others, which are caused by the inhalation of certain fibrogenic dust particles [54], constituting a global health problem. In this sense, the appeal is made to inform the population about the risks of work in certain industries, such as construction. The United States, makes the appeal to the National Institute for Occupational Safety and Health (NIOSH), where they urge publishers, employers and officials to make recommendations to preserve health and prevent lung disease in the population at risk [55].

In this regard, over the last two decades, research has generated information on the many complex pulmonary reactions involved in lung diseases associated with various agents, including mineral dust. Is highlighted that these investigations have involved experimental and clinical physicists and pathologists [56]. The contribution of physics from the point of view of suspended particles (dust) is relevant. Since the size and other physical parameters (density, shape and electrical charge on the surface) of the dust establish the aerodynamic behaviour of the particles and the probability of their penetration and deposition in the various constituents of the respiratory system [56].

3.6 How much does it cost to breathe...to speak, to laugh, to sing?

The lungs make it possible not only to breathe but also to cry, talk, laugh, and run. However, what happens when our lungs cannot perform this function, what are the options for this vital function to continue? Well, when the body does not receive enough oxygen, it needs the supply of this vital element through equipment such as oxygen concentrators or tanks, the cost of which will depend on the amount of oxygen a patient requires. Here is a testimony (J. Castorena, personal communication, 30 November 2022):

"Since 2013 I was diagnosed with idiopathic pulmonary fibrosis, a progressive autoimmune disease that worsened my condition until in June 2020 I was oxygen dependent. This meant renting an oxygen concentrator and having back-up oxygen tanks (in case the electricity supply failed and a portable concentrator, for when I needed to leave my home. On average I was spending USD 350 per month on medical oxygen and I invested USD 2800 on the portable concentrator which only provided 5 $^{L}/_{min}$ 5, which I stopped using in less than a year, because, within a month, my condition worsened, requiring 15 $^{L}/_{min}$ this made me less mobile outside my home. By then, I lost my voice, because my vocal cords were damaged and walking was a strenuous activity, almost a marathon. However, in May 2022, my lungs collapsed, so I required a two-lung transplant (see figure 4), the result of an anonymous and free cadaveric donation. I am fortunate, because thanks to the donor's family, science, biomedical devices and doctors, I am alive.

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Fig. 4. Post-transplant photograph. Source: courtesy of J.Castorena.

Currently, I no longer require medical oxygen; however, keeping my new lungs healthy involves psychoprophylactic treatment (I take 15 medications daily), a daily one-hour pulmonary and physical exercise routine and regular check-ups by a multidisciplinary medical team.

If I had not had this condition, I would never have imagined how valuable vital organs are, also that when we are healthy, we breathe for free, this makes me reflect that we should even take care of the air we breathe; avoid occupational hazards, using personal protective equipment (masks) and avoid damaging our lungs through regular consumption of tobacco or use of vapes. I believe that all human beings are fortunate that we do not have to pay for the air we breathe, because if we did, we would practically have to work to pay for the oxygen, from the air, that we consume every day for the rest of our lives.

3. Conclusions and some considerations

It is clear that this contribution does not cover all the topics related to physics and the lungs. This research team aspired to contribute an aspect scarcely addressed by the teaching of physics: the explanation of the behaviour and functioning of a physical nature, coupled with an explanation of the respiratory physiology of the lungs of human beings. The contribution lies in providing a document for teachers and students that allows them to get to know the complex respiratory system in an elementary way, giving rise to an eventual interest in deepening their understanding. In addition, more importantly, to reflect on the self-care of the lungs.

What the lungs know because of physics' contribution is that:

a) Elasticity is a physical variable present in the lungs, without which the respiratory process would be impossible. Moreover, fortunately, the lung, contrary to the definition, retains, under normal conditions, its primitive shape.

b) In the breathing process, the lungs behave like springs, as a force is required to stretch and compress the lungs causing an initial and final displacement, which is quantified by Hooke's Law.

c) With Laplace's contribution, it can be determined that the lower the alveolar pressure, the better the gas exchange in the lungs.

d) Airflow depends on the diameter of the alveoli, age and size of the individual. Airflow resistance can be analysed with Poiseuille's law and the definition of resistance.

e) ECMO is a sophisticated machine, a work of engineering and science, such as physics, chemistry, and biomedicine; it offers hope for life when the respiratory and cardiovascular systems are compromised.

f) The spirometer is a device whose key variable is a volume measurement, a predictor of lung health and survival.

g) The human body is an open system, and the process of breathing ratifies this; because there is an exchange of matter with the environment (input of O_2) and we release energy in the form of heat and work.

h) The airflow required by a healthy adult, at rest, is between 7 and 8 $L/_{min}$.

i) The physical analysis of airborne particles (dust) is a relevant contribution to lung health, since the size and other physical parameters (density, shape and electrical charge on the surface) make it possible to determine the aerodynamic behaviour of these particles and the probability of their penetration and deposition in the respiratory tract. With this information, the population can take preventive measures to preserve the health of their lungs.

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