Physical Model of the Cardiopulmonary System and its Interactions using the Object-Oriented Multi-Domain Environment SIMSCAPE

Fernandez de Canete, J., Pyzh, M., Garcia-Moral, I.

***Abstract*— Nowadays, cardiovascular diseases together with chronic obstructive pulmonary diseases represent the main causes of natural death. On a physiological level, the cardiovascular and respiratory systems are closely related as the heart and lungs are responsible for providing nutrients to the body and removing waste substances. The use of mathematical models has contributed to a greater extent to gain an insight into the internal process that take place at cardiovascular and pulmonary level. In this paper electro-hydraulic and mechanic-electrical analogies have been employed to model the cardiovascular and respiratory systems using the SIMSCAPE physical modelling environment. Results have been obtained showing an adequate performance both under physiologic and pathophysiologic situations. The objective is to provide the clinician with a benchmark to get valuable information concerning the performance of the cardiorespiratory system and its tight interrelations.**

***Keywords*— Physical Modeling, Electrical Analogy, SIMSCAPE, Cardiorespiratory System,**

I. INTRODUCTION

Cardiac and pulmonary functions are considered vital systems to maintain homeostasis [1]. In order to analyse cardiopulmonary interactions, mathematical models and computer techniques simulation techniques have been used to comprehend the complex interrelations that take place between the cardiovascular and pulmonary function [2].

As to the study of cardiovascular system, several mathematical models have been reported to explain the operation of the cardiovascular system under both physiological and pathological conditions [3]-[4]. As to the aspect of pulmonary dynamics, computer simulation models for the human respiratory system based on mathematical models have also been developed [5]-[6]. As the heart–lung interaction is characterized by a high nonlinear behavior, it is necessary the use of combined cardiorespiratory mathematical models to describe its interrelation, and several related works have been reported to date [7]-[9].

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The use of electrical analogy enables the dynamics of cardiovascular system and respiration to be represented by equivalent circuits that can become more explicit to clinicians.

Several models have been developed employing electrical-hydraulic analogy for the cardiac system [10] and electrical-pneumatic analogy for the respiratory system [6]. It is precisely this approach which facilitates the use of object-oriented based modelling software to capture the physical essence of a model constituted by its individual components and their interconnections, thus defining the underlying dynamics. The object-oriented language SIMSCAPE is integrated with SIMULINK and can import components from MATLAB toolboxes [11]. This programming language has been employed successfully to model many complex systems in physiology [12].

In this paper electro-hydraulic and mechanic-electrical analogies have been employed to model the cardiovascular and respiratory systems using the SIMSCAPE physical modelling environment. Results have been obtained showing an adequate performance under both normal situation and exercise, pulmonary obstruction and aortic regurgitation situations. The objective is to provide the clinician with a benchmark to get valuable information concerning the performance of the cardiorespiratory system and its tight interrelations.

This paper is organized as follows. Section 2 presents a brief description of the cardiopulmonary model used in this research and their interrelations. while in section 3 are detailed the modelled interactions aforementioned. In section 4 it is shown the whole block diagram structure in SIMSCAPE while simulations and relevant results obtained under normal and pathologic conditions are discussed in section 5. Finally, the main conclusions are given in section 6.

II. CARDIOPULMONARY MODEL

Concerning the cardiovascular system, the heart at mechanical level would represent a pump pushing blood to the rest of the arteries and veins, while the arteries and veins would be branching pipelines. Having this in mind, a basic formulation of an equivalent hydraulic model would be direct. Following the same reasoning, lungs perform as mechanical system that push the air in and out during inspiration and expiration provoking the air displacement. Thus, both, could be modelled as mechanical systems, and from here, by using analogies, an electric circuit is easier to be implemented. Therefore, it is said that two systems are analogous to each other when even though the systems are physically different

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and their mathematical model are represented by the same type of differential equations.

The information provided in Table I represents the equivalence between the equations of hydraulic and electric systems by virtue of the electro-hydraulic analogy used throughout the paper.

TABLE I
ANALOGY BETWEEN ELECTRIC AND HYDRAULIC SYSTEMS

Electric equations	**Hydraulic equations**
Voltage $\phi[V]$	Pressure p $[Pa]$
Charge q $[C]$	Volume V $[m^3]$
Current I [A=C/s]	Flow rate $\phi_V[m^3/s]$
Current density j [A/m^2]	Velocity v [m/s]
Electric resistance R [Ω]	Hydraulic resistance R [Ω]

The analogous Windkessel model [13] represents the heart and systemic arterial system as a closed hydraulic system where the pump compresses the water out of the chamber thanks to the air of its inside. There exist three different basic Windkessel models, which are created by a combination of resistors, capacitors and inductors elements with two, three or four elements (Fig. 1). Besides, there are two variable components, the input function $i(t)$ which is the blood flow and output function $u(t)$ that is the blood pressure. Here R refers to the total peripheral resistance, C is the compliance of veins, L is the inertance of arteries and r represents the pulmonary or aortic valve.

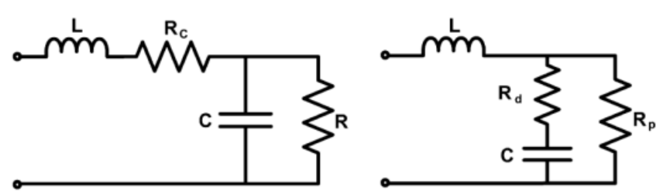


Fig. 1. Scheme of 3rd order Windkessel models used to represent the cardiopulmonary system

SIMSCAPE allows to create physical component models based on physical by arranging key components in order to create electrical, hydraulic or mechanical [11]. SIMSCAPE contains the Foundation Library from where it is easy to design electric circuits by selecting elements from the Electrical Elements, Electrical Sensors and Electrical Sources libraries (Fig.2). Besides these elements, some other blocks allow the connection between SIMULINK and SIMSCAPE.

The dynamics of the blood circulation through the heart and the rest of the body can be represented as an electric analogous circuit (Fig. 3) as is described in [7]. This electrical model consists of a simplified arrangement of several components, namely, an AC power supply $P_v(t)$ representing the left ventricle pressure, a diode (D) which models the aortic semilunar valve, a resistor R_1 standing for the aortic resistance, a resistor R_2 standing for the peripheral resistance, L as an inductance representing the overall inertia of blood, a capacitor C which is the compliance of the arterial system, along with pressure aortic branch $P_{art}(t)$ and at peripheral artery $P_{per}(t)$ and $Q_{art}(t)$ as the flow at aortic level while $Q_{R_1}(t), Q_{R_2}(t), Q_L(t)$ and $Q_c(t)$ represent flows through each of the rest of components of the electric circuit.

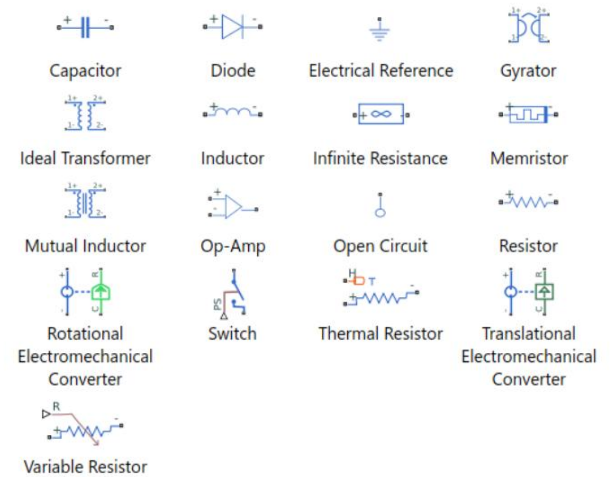


Fig. 2. Electric components belonging to the SIMSCAPE Electrical Library

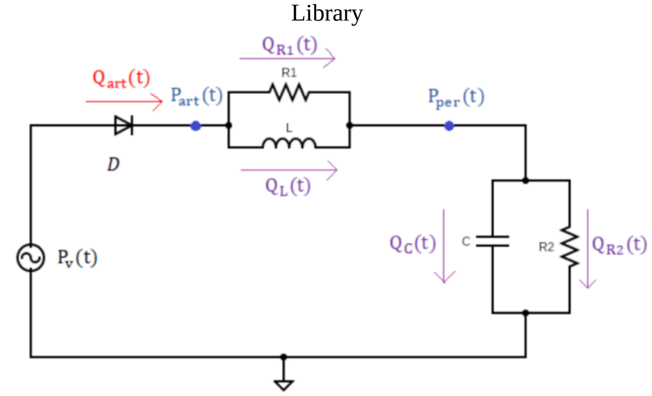


Fig. 3. Schematic representation of the cardiovascular electric circuit

Appropriated values of the electric parameters of the cardiovascular analogous circuit are given in Table II [7].

TABLE II
VALUES OF THE COMPONENTS OF THE CARDIOVASCULAR SYSTEM IN TERMS OF ELECTRIC-HYDRAULIC ANALOGY

Cardiovascular parameters	
$P_V(t)$	$P_V(t) = 120(\sin(\pi f_{HR} t))^{10}$
f_{HR} (hear beat rate at rest)	1.25 $[Hz]$
R_1	0.03 $[\Omega]$
L	0.005 $[H]$
R_2	1.2 $[\Omega]$
C	1 $[F]$

The dynamics of the pulmonary circulation are described by air intake, air inlet and air outlet elements interconnected through the circuit described in [7] (Fig. 4). The system is going to be composed of AC power supply $P_{Lg}(t)$ representing the pressure at the lungs necessary to generate the respiratory cycle, inductance L_{Lg} standing for the overall inertia of the airflow, resistor R_{Lg} as the overall resistance of the airflow, capacitor C_{Lg} which is the overall compliance of the alveoli, along with overall pulmonary pressure $P_{pt}(t)$ and $Q_{Lg}(t), Q_{Rg}(t)$ and $Q_{Cg}(t)$ flows through each of the rest of components of the electric circuit.

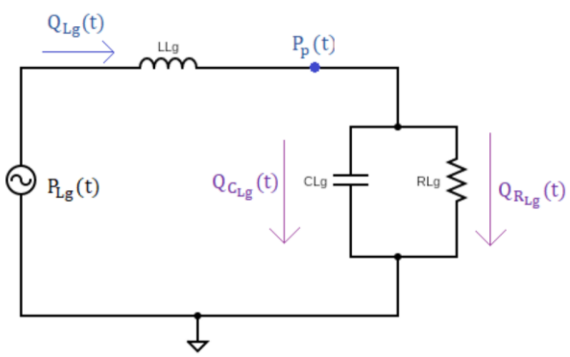


Fig. 4. Schematic representation of the pulmonary electric circuit

Appropriated values of the electric parameters of the respiratory analogous circuit are given in Table III [7].

TABLE III
VALUES OF THE COMPONENTS OF THE RESPIRATORY SYSTEM IN TERMS OF ELECTRIC-HYDRAULIC ANALOGY

Pulmonary parameters	
$P_{L_g}(t)$	$P_{L_g}(t) = (\sin(2\pi f_{BF} t)$
f_{HR} (breath frequency at rest)	$0.25\ [Hz]$
LL_g	$10^{-4}[H]$
RL_g	$2.55\times10^{-3}[\Omega]$
CL_g	$1.45\times10^{-4}[F]$

III. Modelling of Cardiopulmonary Interactions

The interconnection between the cardiovascular and pulmonary systems will be made on the basis of three conditions, the first involving progressive physical exercise, the second involving pulmonary obstruction and the third involving aortic regurgitation.

Physical exercise is mainly driven by the respiratory system which takes in oxygen and transports oxygen to the muscles by the cardiovascular system, thus allowing the body to move. During exercise there is an increase in heart rate $HR(t)$ which is proportional to the oxygen demand required by the body $MR_{O_2}(t)$, which in turn is proportional to the workload $W(t)$.

When physical activity increases and with it the oxygen consumption, there is an increase in heart rate f_{HR} so the greater is $W(t)$ the higher is the frequency to accomplish that work, and also a decrease is produced in aortic resistance R_1 [14].

As for the relation between cardiac and pulmonary function during normal conditions exercise, a proportional rate is set, Finally, simulation of different physical conditions such as walking and running can be implemented by increasing the value of the workload $W(t)$, measured as a percentage.

Severe pulmonary obstruction (COPD) is characterized by the limitations of the airflow rate within the lungs. Specifically, COPD can cause pulmonary hypertension, which represents an increment of pressure in the pulmonary arteries, leading to hypertrophy and failure of the right ventricle [15]. Moreover, COPD can cause increased hypoxemia, an abnormally low partial pressure of oxygen in arterial blood leading to heart rate variability. It is important to mention that the heart rate frequency has a saturation point caused by the fact that the heart reaches a maximum number of beats per minute [16]. Thus, two effects are caused by COPD, namely, cardiac insufficiency due to the failure of the left ventricle causing the drop of $P_v(t)$ and an increase of the heart rate with a saturation limit. Furthermore, to represent different saturation levels, it is necessary to make changes in the resistance R_{Lg} assuming a mild or moderate pulmonary obstruction.

IV. Cardiopulmonary System in SIMSCAPE

As a result of the implementation of the cardiopulmonary system in SIMSCAPE, two physical block diagrams have been created separately, one for the pulmonary system (Fig. 5). and the other for the cardiovascular (Fig. 6)

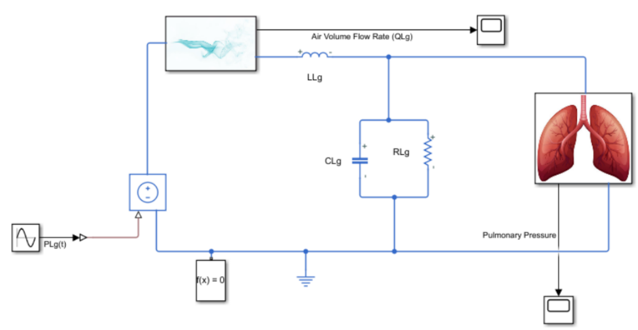


Fig. 5. SIMSCAPE block diagram of the pulmonary system

In order to create situations of exercise, pulmonary obstruction and aortic regurgitation, specific blocks have been created, which enable interaction between cardiovascular and pulmonary system.

As mentioned before, aortic regurgitation will involve a change in closing resistance of the semilunar valve, so there will be a decreasing in blood flow to the muscles along with an increasing in muscle stiffness. For the last case, it is necessary to implement a variable resistor to produce the regurgitation effect as it is shown in Fig. 7.

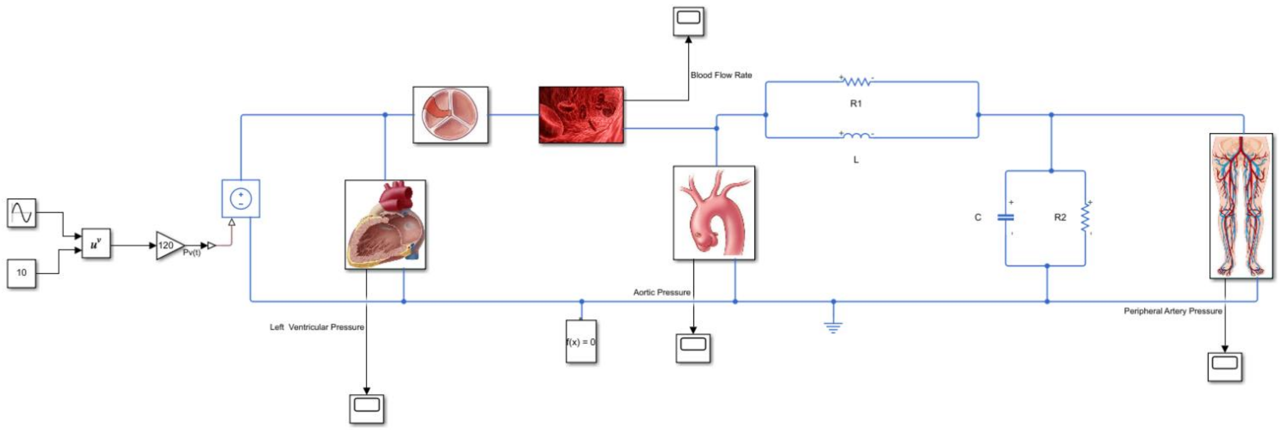
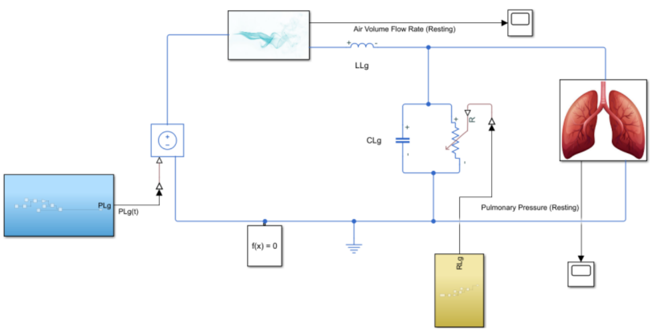
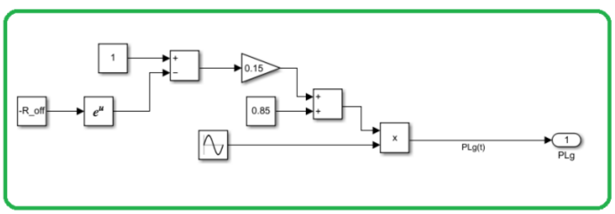


Fig. 6. SIMSCAPE block diagram of the cardiovascular system



(a)



(b)

Fig. 7. SIMSCAPE block diagram of the pulmonary system under a regurgitation scenario (a) and detail of muscle blood flow module (b)

V. Results

The purpose of this section is to test the performance of the under normal exercise conditions and validate the obtained results. For the sake of comparison, the results of [7] are going to be used thought out to validate our results.

The first analysis to start with is that of the response obtained from the cardiovascular system. under normal conditions. An overview of left ventricular pressure, aortic pressure and peripheral pressure is given in Fig. 8.

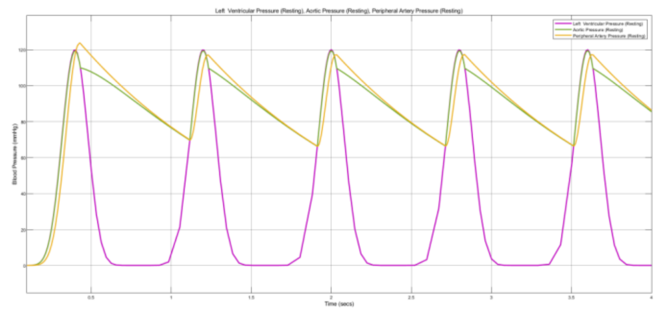


Fig. 8. Cardiovascular pressures evolution under normal conditions

Results obtained in normal conditions are in agreement with those of [7] and with physiological values that can be find in literature and textbooks.

Regarding the pulmonary system, the pulmonary pressure is starting to increase until the volume flow rate reaches the maximum amount, during the inspiration phase and expiration phase is then followed (Fig. 9).

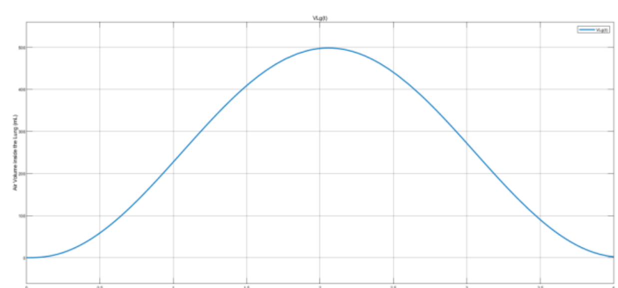


Fig. 9. Air volume inside the lung under normal conditions

In case of physical exercise, there is an increase in heart rate and, in turn, a decrease in aortic resistance (Fig. 10). Therefore, a coupled effect for the respiratory and pulmonary systems will appear. For the simulation of physical activity corresponding to walking and running with variable values of workload $W(t)$ (Fig. 11).

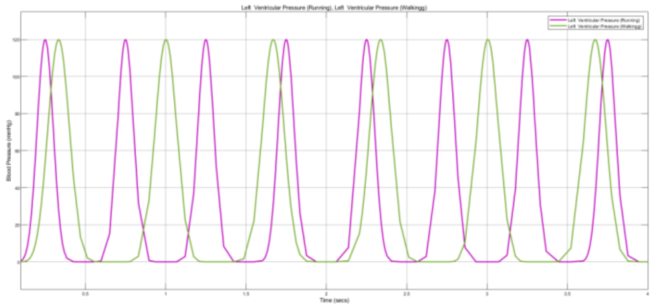


Fig. 10. Ventricular pressure evolution under exercise conditions

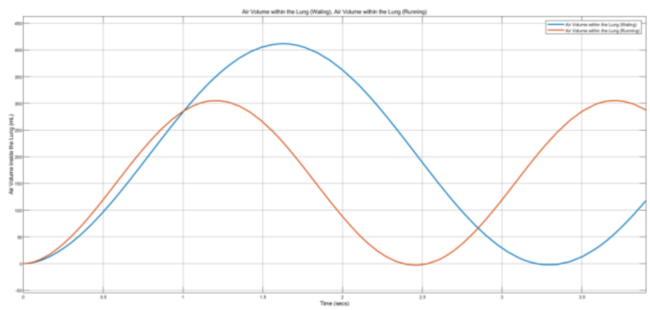


Fig. 11. Air volume during exercise

In case of aortic regurgitation, the values obtained for different cases of closing valve resistance are compared. In case of severe aortic regurgitation, the percentage obtained of regurgitation volume is triple of that of mild case. Tests performed for both mild and severe regurgitation show blood flow reduction (Fig. 12).

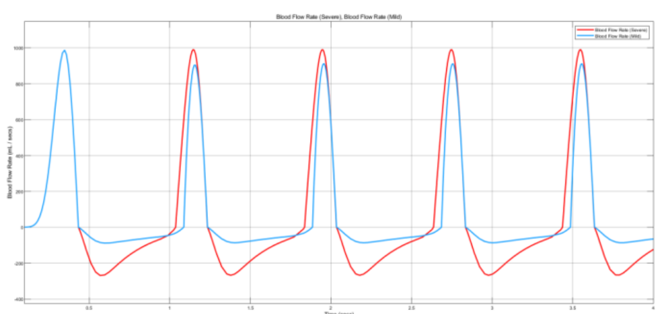


Fig. 12. Blood flow rate under aortic valve regurgitation cases.

Finally, in case of pulmonary obstruction, the higher is the respiratory resistance, the lower is the amount of air that can be taken in during inspiration, which is entirely normal since obstruction of the airways decreases the air volume (Fig. 13).

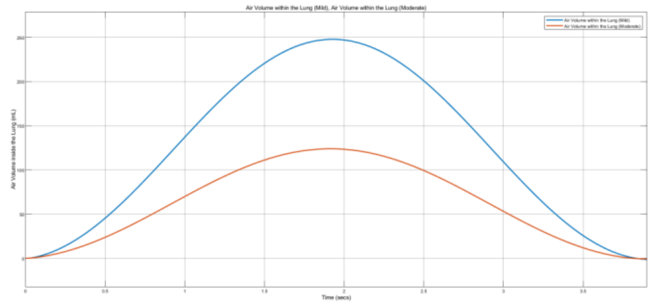


Fig. 13. Air volume in the chronic obstructive pulmonary disease.

VI. Conclusions

An object-oriented cardiopulmonary model has been realized consisting of the cardiovascular and pulmonary systems separately but interrelated each other. The use of electrical analogies has enabled SIMSCAPE to build a physical block diagram interconnecting electrical blocks to modelling and simulating the cardiopulmonary system dynamics during exercise, even in case of malfunction in the heart function or the existence of lung diseases. Thus, there is no need for the patient to undergo any test in-vivo but in-silico. Besides, the simplicity of the cardiopulmonary model permits the physician, or appropriate personnel to interpret to interpret the results of the system under study without a specific mathematical knowledge.

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