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Object-Oriented Programming for Modeling and Simulation of Systems in Physiology

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Abstract**—**Object-oriented modeling is spreading in current simulation of physiological systems through the use of the individual components of the model and its interconnections to define the underlying dynamic equations. In this paper we describe the use of both the SIMSCAPE and MODELICA simulation environments in the object-oriented modeling of the closed loop cardiovascular system. The performance of the controlled system was analyzed by simulation in light of the existing hypothesis and validation tests previously performed with physiological data. The described approach represents a valuable tool in the teaching of physiology for graduate medical students.

Keywords**—**Object-Oriented Modeling, SIMSCAPE Simulation Language, MODELICA Simulation Language, Cardiovascular System.

I. INTRODUCTION

THERE are a considerable number of specialized and general-purpose modeling software applications available for biomedical studies. A non-exhaustive list of such tools is provided in [1], divided into structure-oriented and equation-oriented applications.

Object-oriented languages can offer many advantages facing modeling and simulation tasks when complex multidisciplinary systems are given [2]. The object-oriented approach can offer many advantages in physiological system modelling when dynamics are given by a set of differential algebraic equations (DAE). This object-oriented approach can be implemented using modelling language such as MODELICA [3], or SIMSCAPE [4] among others, which allow the system, subsystem, or component levels of a whole physiological system to be described in increasing detail using a hierarchical structure.

Cardiovascular modeling and simluation present a particular challenge in that it requires both a multi-scale and a multi-physics approach. Several mathematical models of the closed loop cardiovascular system have been developed [5], [6] and distinct simulation development tools have been used for graphic notation of the structure of physiological regulation's systems, including that of the cardiovascular control system [7], [8].

In this paper we describe the use of the object-oriented modeling to both modeling and simulation in Physiology. We have applied both the SIMSCAPE and the MODELICA programming tools and comparison has been made for the simulation of the closed loop cardiovascular system. The results were obtained under both physiological and pathological conditions, taking into account the validation tests previously performed with physiological data.

II. THE OBJECT ORIENTED MODELING APPROACH

SIMSCAPE and MODELICA are object-oriented languages for modelling continuous complex physical systems for the purpose of computer simulation, and are primarily based on physical modeling rather than mathematical modeling. They also have multi-domain modelling capability, meaning that model components corresponding to physical objects from several different domains can be described and connected.

The most important difference with regard to the traditional block-oriented simulation tools as SIMULINK is the different approach to connecting the components of the physical model. Thus, as an interface, a special-purpose connector defines the variables of the model shared with other sub-models, without prejudicing any kind of computational order. In this way the connections can be thought of as one of the key features of oriented-object modeling along with the inheritance capabilities, thus enabling the effective reuse of the model.

In SIMSCAPE, a model is defined as a collection of physical blocks which must be appropriately connected to define the dynamic system. The specific connection diagram together with the conservation laws applied determines the system dynamic equations. It must be emphasized that 'ode15s' and 'ode23t' are the only numerical integration methods allowed by SIMSCAPE to run the model [4].

The modeling approach in MODELICA is based on the decomposition of the system into components that are as simple as possible (classes) and then, starting from the bottom, connecting of the basic components into more complicated ones, until the top-level model is achieved. The default integration method used in MODELICA is the DASSL code as defined by [9], but other methods are also available, such as Runge-Kutta and BDF-based methods.

This physical approach supports two types of variables, "effort" variables which are measured with a sensor connected in parallel to a component with respect to a reference, and "flow" variables, which are measured with a sensor connected in series to a component (Fig. 1). The sum of effort variables in a closed loop is null, while the sum of flow variables flowing into a branch point equals the sum of all its values flowing just as the Kirchoff laws state.

Both programming object-oriented languages are similar in its capabilities, while MODELICA enables the model implementation in textual code so as DAE solution can be

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easily obtained with DASSL [3].

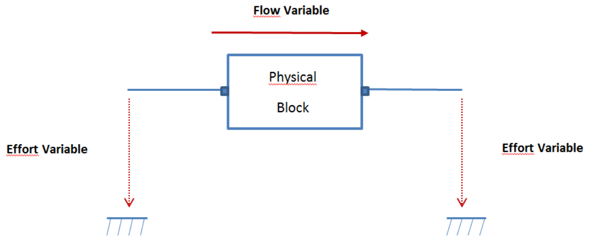

Fig. 1 The effort and flow variables used in Physical Modeling

III. MODEL OF THE CARDIOVASCULAR SYSTEM

As a first approach, we can consider the cardiovascular system as a closed loop circuit constituted by the systemic and the pulmonary circulation in series with the heart pump configured by two ventricles with two valves each (Fig. 2).

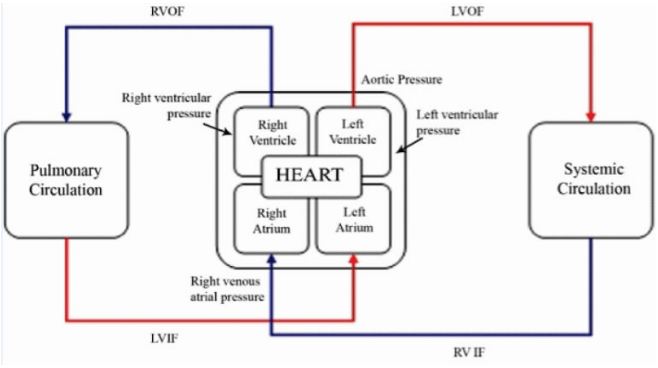

Fig. 2 Block diagram of the cardiovascular system

The model used here is based on previous studies by [10], where the cardiovascular system is proposed formed by seven compartments, each one modelled using a mathematical relationship between blood volume, input flow rate $V_i(t)$ and output flow rate $F_{i_{in}}(t)$ relative to the *ith* compartment given as

$$\frac{dV_i(t)}{dt} = F_{i_{in}}(t) - F_{i_{out}}(t) \qquad i = 1 \cdots 7 \tag{1}$$

with flow rate $F_{ij}(t)$ between compartments *i* and *j* defined in general by

$$F_{ij}(t) = \frac{P_i(t) - P_j(t)}{R_{ij}} \qquad i = 1 \cdots 7, \ \ j = 1 - 1 \tag{2}$$

or in the case of flow rate through a valve by

$$F_{ij}(t) = \frac{lim(P_i(t) - P_j(t))}{R_{ij}} \tag{3}$$

where R_{ij} stands for the resistance to the flow between compartments *i* and *j*, while the function $\lim(x) = \max(x, 0)$.

The relation between pressure $P_i(t)$ and volume $V_i(t)$ in each systemic and pulmonary compartment is given by

$$P_i(t) = E_i V_i(\mathrm{t}) \qquad i = 1 \cdots 5 \tag{4}$$

where E_i stands for the elastance of compartment i, while heart contraction and ejection processes are described in each ventricle according to variable elastances as is referred in [10].

IV. THE CARDIOVASCULAR MODEL IN SIMSCAPE

In order to implement the SIMSCAPE cardiovascular model, we can relate every anatomic property of the circulatory system with the element of the analog electronic circuit (Fig. 3). On one hand, each ventricle will be described as an isovolumetric time-dependent pressure generator in series with a time-varying elastance and a resistance. The unidirectional character of the inlet and outlet heart valves is modeled by an ideal diode in series with an electrical resistance. The atrial elastic characteristics are included in the venous compliances, which are modeled as capacitances in the circuit. On the other hand, the systemic and pulmonary circulations will be simply described by an RLC two-stage network, where resistances and inductances represent inertial and viscous properties of the blood flow, while capacitances correspond to the elastic properties of the vessel walls.

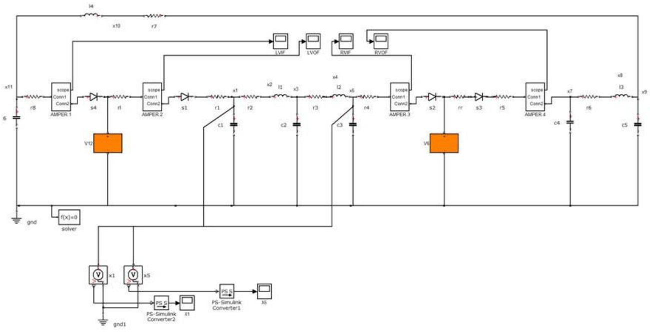

Fig. 3 The SIMSCAPE model of the cardiovascular system

This SIMSCAPE modeling approach allows modifications to be made to each component in a more intuitive and simple way than when causal block diagrams are used. In fact, despite the nonlinearity of the cardiovascular model, it is extremely easy to follow the proper branches of the circuit in order to identify the very different parts of the cardiovascular system. We can clearly appreciate up to eight subsections that are made up of either RLC stages or RC-diode stages, due to the compartmental strategy used to model the cardiovascular system.

V. THE CARDIOVASCULAR MODEL IN MODELICA

Each of the constitutive components of the cardiovascular system defined in Fig. 1 was coded in MODELICA starting from the set of equations (1) to (4) by gathering the necessary blocks from the MODELICA general purpose libraries together with those previously defined by the user (Fig. 4).

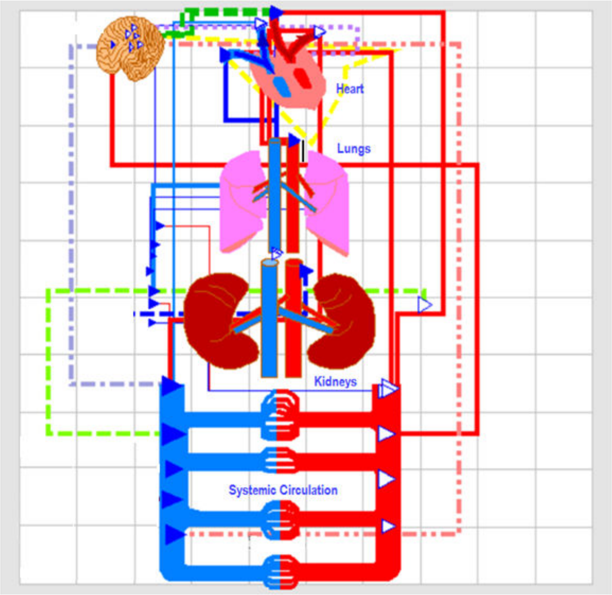

Fig. 4 The MODELICA model of the cardiovascular system

In the same way the components with valves were defined by incorporating the variable elastance of the ventricular compartments into a table with time as the input variable, with a pulse-shaped behaviour function that is used to generate the heartbeat rhythm.

It is important to highlight that the behaviour of each compartment is described by a similar set of equations, so it is only necessary to model the compartment's dynamics using one block, which can then be reused (inheritance). In this common block, inputs are defined as all external variables to the compartment that are involved in any kind of exchange with the compartment, while outputs are referred to as the compartment variables that interact with the rest of the compartments.

VI. SIMULATION RESULTS

The results have been obtained by applying the full cardiovascular model depicted in Fig. 1 under both physiological and pathological conditions, assuming the validation tests previously performed with physiological data as defined in [10].

In first place it is shown the results obtained with the SIMSCAPE model under physiological conditions. In Fig. 5 it is shown the aortic pressure evolution obtained under normal conditions for the set of patient's parameters detailed in [10], where it can be seen a pair of cardiac cycles. The arterial pressure waveform exhibits the aortic valve closure phenomenon, due to the unidirectional valve modelling.

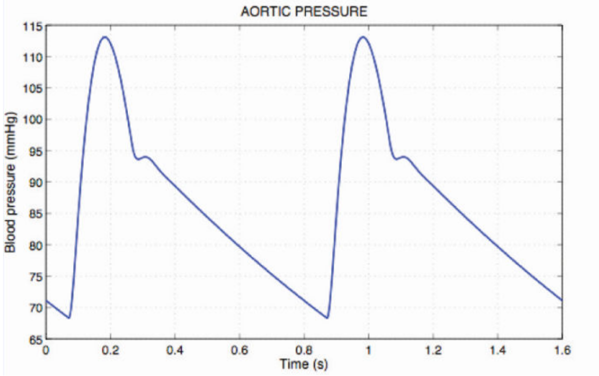

Fig. 5 Evolution under normal conditions of aortic pressure in SIMSCAPE

Fig. 6 shows the cardiovascular response to a doubling of the peripheral systemic resistance during the diastole in MODELICA, and it can be observed an increase in the aortic pressure.

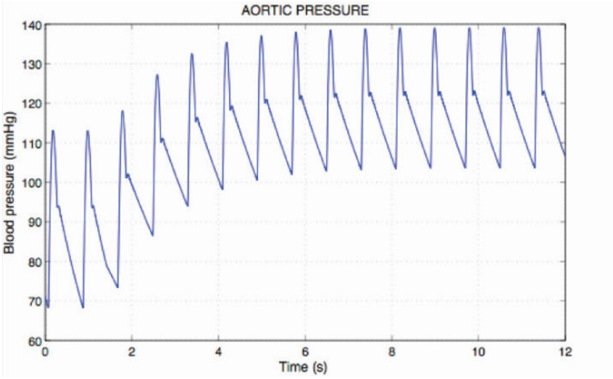

Fig. 6 Evolution after imposing a sudden change in value of systemic resistance in MODELICA

A case of hypervolemia has also been included in Fig. 7, where a sudden rise of the blood volume results in a fluid inertance augmentation, causing a large increase in the aortic pressure observed within a short transition time.

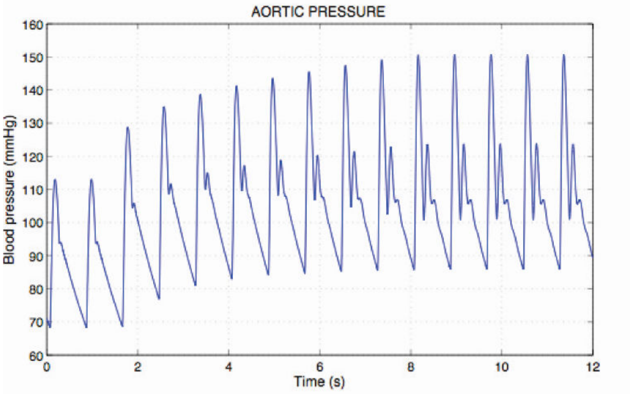

Fig. 7 Evolution during induced hypervolemia by increasing the inductances in MODELICA

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VII. CONCLUSIONS

In this paper we describe the use of both the SIMSCAPE and MODELICA simulation environments in the object-oriented modeling of the closed loop cardiovascular system.

SIMSCAPE enables the whole structure to be organized as components with well-defined connections, so that the system dynamics are embedded in the connection diagram. The depiction of the model in this simulation environment resembles the physical reality of the modeled world more closely than the classical interconnected block schemes in SIMULINK. MODELICA language uses a hierarchical modelling strategy, so that modeling effort is considerably reduced and the model reuse is facilitated.

Simulation models are more legible in SIMSCAPE or MODELICA, which can be both considered as suitable tools to the modeling of physiological systems.

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