A MODEL OF THE VENTRICULAR ACTIVITY USING BOND GRAPHS

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Abstract: A model of the ventricular activity using the Bond Graph formalism is presented. This model considers a simplified description of the ventricular geometry and the electromechanical phenomena occurring during cardiac contraction. Besides the interactions between the mechanical structure and the blood flow are considered. Finally the simulations obtained with the model are compared with real data.

Keywords: Biomedical systems, Bond Graphs, Medical applications, Physiological models, Simulation

1. INTRODUCTION

Heart diseases are the first cause of death in western countries (about 30%). The understanding of cardiovascular diseases can help to elaborate methods that allow early detection of risky events. Modelling in medicine plays more and more a major role. In fact, models could lead to a better comprehension of cardiac pathologies. It can also help to analyse non-invasive signals to determine indicators that help to diagnosis. This work presents a model of the left ventricular activity that takes into account several energy domains, especially the structure-fluid interaction.

Many models of the left ventricle have been already published. Some of them are based on a global description of the cardiac activity as a single elastance model that has often been used in the literature (Guarini *et al*, 1998 ; Palladino *et al*, 2002). Although these kinds of models give pretty good results, they are not able to consider the geometrical characteristics that influence the ventricular performance. The cardiac fibre function has also been described (Montevecchi,, 1987), allowing the definition of whole heart models by means of differential equations (Redaelli *et al*,1997). The finite-element method (FEM) is also often used as computational method for ventricular models simulations (May-Newman K.,1998, Vetter, 2000, Kerckoffs, 2003). This kind of representation gives broadly good results as precise indications on the mechanical behaviour. However, the FEM requires big computational resources, the model modification is difficult and, as a consequence, their clinical applicability is limited. Besides, the interactions between energy domains are difficult to consider. Bond Graphs appear as a good approach since one formalism can be used for all energy domains. Bond Graph models of the ventricle have already been presented (Lefebvre, 1999; Diaz-Zuccarini, 2003, Fakri, 2005). The interest resides in the fact that the cardiac fibre contraction is described using Bond Graph properties. However, in the above mentioned works, the electrical activation is not realistic enough to study some cardiac pathologies, and the interaction between the hydraulic and mechanical activity and the spatial variations of the mechanical and hydraulic properties are completely ignored.

Cardiac geometry of models can be based on real data (Nash, 1998). This approach is interesting but the flexibility is considerably reduced. In this work, the ventricular shape is described analytically. The size and the shape can be changed easily. It is also possible to study the influence of these parameters (shape, size) on cardiac performance. Cylindrical models have been used in the literature, by Redaelli *et al* (1997) to study the influence of cardiac performance on coronary circulation, by Taber *et al* (1996) to analyse the ventricular torsion. Although the cylindrical model is a good approximation, the ellipsoidal geometry is closer to the anatomical structure. This geometry has been also largely used in the literature to analyse the electrical propagation during contraction (Szathmary *et al*, 1994 Franzone *et al*,1998) or ventricular torsion (Taber *et al*, 1996).

This paper shows how Bond Graph method can be used to model and simulate a physiological system. The ventricular activity is first presented. Then, the model is described: the mechanical and the hydraulic aspects. Finally, the simulation results are reported and compared with real data.

2. THE MECHANICAL ACTIVITY OF THE HEART

The heart is a muscular pump system that pushes blood to all parts of the body. It is divided into four chambers: the two top chambers are called atria, and the lower chambers are called ventricles (figure 1). The atria collect the blood that enters the heart and push it to the ventricles, which eject blood out of the heart into the arteries. These heart chambers alternate periods of relaxation called diastole and periods of contraction called systole. The mechanical activity of the heart is controlled by a preceding electrical activity. This process is called the cardiac excitation-contraction coupling.

The cardiac muscle (or myocardium) is composed of cardiac myocytes, which are specialized muscle cells. These myocytes are made of myofibrils that contain sarcomeres, which are the elementary contractile elements. Sarcomeres can contract only if there is enough intracellular calcium available. This concentration rises during the action potential, which is produced through changes in membrane ion permeabilities. The calcium entrance into the cell increases the intracellular calcium concentration and lead to the sarcomeres contraction that converts electrical energy into mechanical energy.

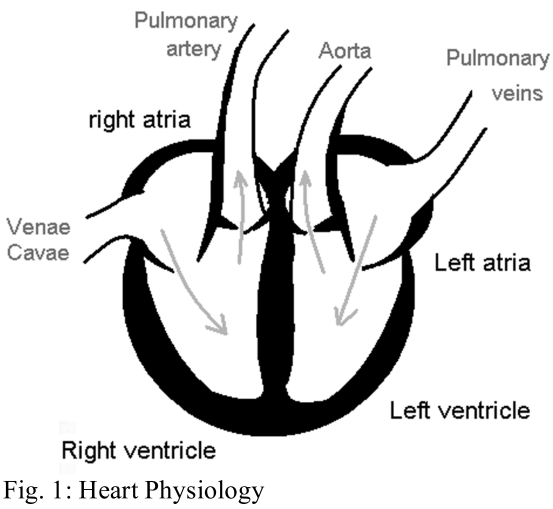

Fig. 1: Heart Physiology

3. A MODEL OF THE LEFT VENTRICLE

The ventricular model should take into account the interactions between the hydraulic and mechanical activities. This last one is activated by the cardiac electrical activity as seen previously.

3.1 Mechanical description.

The mechanical ventricular activity is classically divided into active and passive properties. Active properties are related to force development in the contractile elements of cardiac cells, which is due to the intracellular calcium concentration; whereas, passive ones are due to myocardium organisation (fibres, collagen…)

3.1.1 Passive properties

The ventricle is assimilated to a thick-wall structure. A wall segment that is under the influence of large deformations is first considered. The deformation is supposed to be exclusively radial. So, supposing that, in spherical coordinates, a material particle in the undeformed state (R, Θ, Ψ) goes to (r, θ, φ) in the deformed state, we have:

$$r = r(R); \qquad \theta = \Theta; \qquad \varphi = \Psi \quad (1)$$

Then deformation gradient tensor $\boldsymbol{F}$ and the left and right Cauchy-Green tensor ($\boldsymbol{B}$,$\boldsymbol{C}$) can be obtained. As the deformation is known, the strain in the principal direction can be expressed. Moreover, wall segment is assumed to be incompressible:

$$\lambda = \lambda_\theta = \lambda_\varphi = \frac{r}{R} \qquad (2)$$

and the material is supposed to be hyperelastic. So, it is possible to determine the relation between stress and strain:

$$\sigma = -pI + 2F\frac{\partial W}{\partial C}F^T, \qquad (3)$$

where p is the hydrostatic pressure, I is the identity matrix, C is the Cauchy-Green tensor, F deformation gradient tensor and W is the strain energy function. Different functions W have been proposed and enumerated in the literature (Munteanu *et al*, 2002, Mourad, 2003). Most of them are based on knowledge on the ventricle structure and have been measured experimentally on myocardial tissues. The greater part of these models takes into account cardiac fibre orientation, so the material is supposed to have an anisotropic behaviour. For example, some models are based on the hypothesis of orthotropy. Hunter *et al* (1998) propose a law called "pole-zero" that is based on a laminar description of the myocardium. Guiccione *et al* (1995) introduce an exponential law. However, the preceding formulation is complex and utilization is difficult because the strain energy function is defined in the fibre coordinates. The material can be also considered to be transversely isotropic. For example, Lin (1998)