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BIVENTRICULAR PACEMAKER SYNCHRONIZATION: A NUMERICAL CARDIOCIRCULATORY MODEL APPLICATION

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INTRODUCTION

Biventricular pacemakers are used for cardiac resynchronization therapy in order to treat the delay in ventricular contractions that occurs in patients with severe heart failure (ejection fraction < 35%, QRS duration > 130ms) and with bundle branch blocks. These diseases affect 600,000 patients in Italy and there are 87,000 new cases every year [1]. Resynchronization therapy tends to restore the normal coordinated pumping action of the ventricles by overcoming the electrical conduction delay by using biventricular pacemaker. It has been observed that implanting a biventricular pacemaker improves quality of life and physical activity resistance increasing ejection fraction. But it is noted that 30% of patients doesn't (do not?) have an improvement because of an absent or incomplete response. Conventional biventricular pacing have three leads: one placed in the right atrium, the second one in the right ventricle and the last in a vein on the surface of the left ventricle. However it is not clear if this solution can completely guarantee inter-ventricular and atrio-ventricular synchronization also considering that synchronization must be specific for each patient. In fact, assuming that pacemaker is correctly placed, every patient presents different clinical responses like modest improvement in exercise tolerance and quality of life, congestive heart failure severity reduction, echo measures and neurohormones.. The aim of this work is to simulate advanced heart failure and severe arrhythmia, and to optimize cardiac pacing with biventricular pacemaker. The numerical model of cardiovascular system, CARDIOSIM© [2] enables to simulate different disease conditions due to different degrees of pathophysiological impairment together with their effect on cardiovascular function.. It has been modified to study the effects of ventricular synchronization.

METHODS

Mathematical model was implemented by CARDIOSIM©, which is a software simulator (developed by the Institute of Clinical Physiology C.N.R.) of the human cardiovascular system. This numerical simulator reproduces the most important circulatory phenomena, in terms of pressure and volume relationship. It has a modular structure including the left and the right heart, the systemic arterial (pulmonary) section, the systemic (pulmonary) venous section and the coronary section. Entire circulation is described by a lumped parameter model, based on Starling's law for the heart. In this simulator, ventricular and atrial characteristics are described by variable elastance models [3,4]. The time-varying ventricular elastance $elv(t)$ is a function of the characteristic elastance during ventricular systole ($Elvs$), ventricular diastole ($Elvd$) and activation function $alv(t)$:

$$elv(t) = Elvd + \frac{Elvs - Elvd}{2} alv(t)$$

The activation function describes the contraction and the relaxation changes in the ventricular muscle:

$$\mathrm{alv}(t) = \begin{cases} 1 - \cos\left(\dfrac{t}{T_T}\pi\right) & 0 \le t \le T_T \\ 1 + \cos\left(\dfrac{t - T_T}{T_{TE} - T_T}\pi\right) & T_T < t \le T_{TE} \\ 0 & T_{TE} < t \le T \end{cases}$$

Where T_T is the T wave peak time in ECG signal, T_{TE} is the T wave end time in ECG signal and T is heart period [4]. The model of right ventricle is similar to that for the left side, except the values of parameters that are different.
The time-varying atrial elastance *ela*(t) is also a function of the characteristic elastance during atrial systole (E*las*) atrial diastole (E*lad*) and activation function *ala*(t), like the one presented for left (and right) ventricle. The activation function describes the contraction and the relaxation changes in the atrial muscle:

$$ala(t) = \begin{cases} 0 & 0 \le t \le T_{PB} \\ 1 - \cos\left(\dfrac{t - T_T}{T_T} 2\pi\right) & T_{PB} < t \le T_{PE} \\ 0 & T_{PE} < t \le T \end{cases}$$

Where T_{PB} is P wave begin time in ECG signal and T_{PE} is the P wave end time in ECG signal [4]. The model of right atrium is similar to that for the left side, except the values of parameters that are different. The block diagram of the whole model, including bi-ventricular pace maker model, is reproduced in Fig.1.
After the software implementation, it has been simulated the pathological conditions and the clinical response of three patients affected by idiopatic or post-ischemic dilatative cardiopathy with interventricular desynchronization. Pacing has been chosen to improve hemodynamic conditions of each patient starting from his pathological conditions. The analysed variables include pressures, flows, volumes and pressure-volume loops.

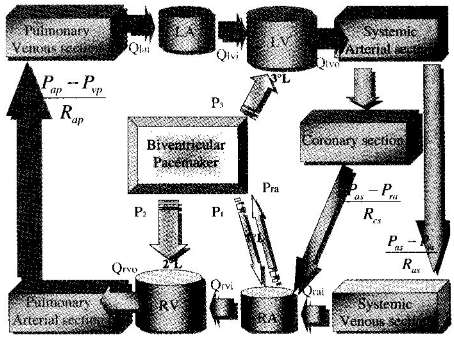

Fig.1. Picture shows the schematic block representation of the interaction between biventricular pacemaker and cardiovascular system. P is the pressure, Q is the flow, R is the resistance and L are the leads. Subscripts: ap pulmonary arterial, vp pulmonary venous, as systemic arterial, vs systemic venous; l left, r right, a atrium, v ventricle, i input and o output.

RESULTS AND DISCUSSION

The model developed permits to analyze the influence of pacemaker synchronization on hemodynamics. The study of ventricular p-v loop has shown that in the case of idiopatic dilatative cardiopathy, changing the systole beginning time or its durations yields a larger ventricular loop and a higher cardiac output. The same situation can be noted varying cardiac elastance and cardiac stiffness. Considering that diastolic elastance depends on stiffness, a higher cardiac stiffness realizes the case of post-ischemic dilatative condition. In conclusion, the model enables to calculate the synchronization related with the specific patients using clinical parameters, mainly hemodynamic variables.

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