UNLOADING THE HEART WITH PULSATILE AND NONPULSATILE IMPLANTABLE ASSIST DEVICES: A COMPUTER SIMULATION STUDY

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Introduction

Both pulsatile and nonocclusive continuous flow pumps are currently used to assist the circulation in patients with terminal heart failure. These totally different types of blood pumps, however, exhibit very different flow patterns and also unloading and interaction mechanisms with the natural heart. To investigate these interactions under reproducible conditions we developed a computer model of the circulatory system including various types of blood pumps. In this overview, the model and some simulation data particularly on the interaction of the heart with the assist pump will be presented.

Methods

Model Description

The computer model consists of three major components: 1) the numerical representation of the circulatory system; 2) the numerical model to mimic the LVAS; and 3) a tool for parameter variation and data monitoring, which allows to perform sets of simulations and to interpolate the results.

Circulatory System: The model of the circulatory system consists of six main segments: The left and right ventricle, the left and right atrium, the pulmonary and the systemic vascular system. The left and right ventricular model are based on the same numerical structure, yet with different parameter settings. The boundaries for cardiac contraction and thereby for the PV-loops are given by the EDPVR (End Diastolic Pressure Volume Relation) and the ESPVR (End Systolic Pressure Volume Relation /2, page 159/).

LVAS: In a first approach the continuous LVAS was modeled by differential equations for both the electromechanical and the hydraulic part of the system similar to /4/. However, modeling of the pump based on characteristic curves, which were derived from the hydraulic model, exhibited better accuracy. The load dependent speed behavior was mimicked by a PI-control element. The computer model of the pulsatile LVAD is also based on characteristic curves. The cannulas (with apical inflow and aortic outflow) were modeled with their friction, inertia, and some elastic capacity, with a pressure dependent variable resistance at the inflow to mimic eventual suction effects /1/.

Monitoring and calculation of derived parameters: All pressure and flow pattern and derived data like PV-loops, TTI (Tension Time Index), DTTI (Diastolic Tension Time Index) and EVR (Endocardial Viability Ratio) can be observed online /1/, /7/, /10, page 171/. However, it must be considered, that these indices assume natural coronary perfusion condition without unloaded ventricle, and are therefore only limited applicable in the case of ventricular assist. Other parameters, which are better compatible with the assist situation, include EW (External Work = area within the PV loop), PE (Potential Energy = area within ESPVR, EDPVR and diastolic part of the PV-loop) and PVA (Pressure Volume Area = EW + PE) /6, page 171-229/, /7/. PE correlates well with the oxygen consumption in normal and also in ischaemic hearts /8/, /9/, /10/. However, at high filling volumes nonlinear effects of ESPVR considerable influence the calculation of PE. Further, the ratio of EW/PE can be considered as an indicator for the ventricular working efficiency.
Results

It is well known that the flow provided by an implanted LVAD has to be handled carefully to avoid overloading of the right ventricle. Whereas the left ventricle is rather uncritically, it is strongly relieved by the continuous working device. So it was nearby to focus our observation on the heart work indices concerning the right ventricle. The question which has to be answered is, how the pump can be adjusted to provide the patient with appropriate flow without overloading the right ventricle. With the computer model it was found that the right ventricular external work has a distinct maximal value. And the external work correlates with the best efficiency of the right ventricle. To answer the previous asked question it has to take into consideration that the left ventricular contractility changes during the rehabilitation of the patient, and is also different for each patient. In attention on this fact the dependency, of the maximal right ventricular work, from the left ventricular contractility was observed (Figure 1). For that four different amounts of contraction (33%, 50%, 65%, 80%) where used. The Figure 1 shows the results in a three-dimensional graph over pump speed and CVP. It is seen that the distinct maximal of right ventricular external work shifts from highest pump speed of 12000rpm at lowest left ventricular contractility of 33% down to lowest pump speed of 7500rpm at 80% of left ventricular contractility.

Discussion

The clinical experience shows that after implant the flow provided by the LVAD has to be rather low. This seems to help the right ventricle to adapt on the new situation. But the simulation draws a picture where left and right ventricle has lowest energy cost and highest effectiveness on maximum pump speed. A theory is that it is suitable to increase the flow when this reduces the PVP. So long as an increased pump speed causes a decreased PVP, a benefit for the right ventricle is established. Because the external work of the right ventricle gets increased, whereas the potential energy only increases slightly. Accordingly the right ventricular efficiency, which is defined as EW/PE, increases.

It has to take into account that the right ventricle efficiency decreases very fast when the PVP increases, and the PVP are controlled by the pump speed dependent of the left ventricular contractility. If the pump speed is decreased and the left ventricle is able to take over the blood flow from the pump, so the right ventricular efficiency keeps constant.

So for best right ventricular efficiency it would be necessary to decrease the pump speed if the left ventricle recovers after implantation.

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References


Figure 1: Changes of right ventricular external work at four different left ventricular contractilities during variation of CVP and pump speed.