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Control Algorithms for Rotary Blood Pumps Used in Assisted Circulation

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This work presents a review of the systems, methods, and algorithms for assisted circulation control published in the literature within the last five years. Control systems used in current clinical practice are described. Algorithms for evaluation, adjustment, operation mode control, and physiological control of the ventricular assist devices based on rotary blood pumps are discussed.

Introduction

Ventricular assist devices (VADs) proved to be effective for therapy of acute cardiac insufficiency as an alternative to heart transplantation [1-4]. Different pathophysiological disorders of the cardiovascular system require different therapeutic strategies to be applied for their treatment using various types of available VADs [5-7]. Implementation of the strategies, automated control of VAD within the framework of the selected strategy, improvement of patient's quality of life, and prevention of specific problems accompanying application of an implanted rotary blood pump (RBP) require various algorithms, methods, and systems of control to be developed. The goal of this work was to review the systems, methods, and algorithms for assisted circulation control published in the literature within the last five years. Similar reviews were published previously [8-10]. In particular, several classifications of control systems for ventricular assist devices were suggested in these reviews. In contrast to the previous works, the main goal of the present study was to discuss the capacity and advantages of VAD control systems. Control systems used in current clinical practice are also described.

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VAD Control Systems in Clinical Practice

The blood circulation rate through the HeartWare HVAD and HeartWare MVAD pumps is assessed by indirect methods from the rotor rotation rate, motor current, and hematocrit [11-15].

The Jarvik 2000 axial pump allows the patient to adjust the pump speed [16, 17].

In the HeartMate II pump [18] the pump capacity is assessed from the pump power and speed.

In the HeartAssist 5 axial pump an ultrasonic flow sensor attached to the output cannula is used to measure the circulation rate [19].

Systems for Estimation and Control of the RBP Capacity

The sensorless method for estimation of the centrifugal blood pump capacity suggested in [20] was based on measurement of the twisting moment and the rotor rotation rate. The absolute error of estimation of the flow rate within the range of 0-10 L/min in water and viscous liquid did not exceed 0.51 and 0.77 L/min, respectively.

Another method for estimation of the centrifugal blood pump capacity was suggested in [21]. This method is able to estimate the dynamics of the ventricular restoration. The method is based on a hydrodynamically tested dynamic pump model described by the following equation:

$$Q = aI + bI^2 + cI^3 + d\omega + e\omega^2 + g\omega I + h\omega^2 I + k - m\frac{d\omega}{dt},$$

where Q is the pump capacity; I is the electric current intensity; ω is the pump speed; a-m are coefficients. The mean difference between the estimated and measured values of the mean pump capacity under dynamic conditions was (0.06 ± 0.31) L/min. The flow characteristic of a pump under dynamic conditions contains information on the interaction between the heart and the pump. This allows the diagnostic indices of contractility of the heart ventricles to be derived from the flow characteristic.

An algorithm for increasing the pulsation by the cardiac cycle modulation of the RBP speed was suggested in [22]. The algorithm was hydrodynamically tested at a contraction rate of 140 bpm using a Micromed DeBakey pump. The pump speed was modulated to provide a pump capacity equal to the capacity at invariable speed. The suggested algorithm allows the pulsation index to be doubled without changing the mean aortic pressure and the pump capacity.

A controller of the implanted RBP capacity was suggested in [23]. A dynamic model was used to estimate the pump capacity from the pump speed and the motor current. The main goal of the controller was to adjust the pump capacity to the required level. The suggested controller was successfully tested using a mathematical model of the cardiovascular system.

Systems for Controlling the RBP Operation Mode

The control systems are used to monitor and control the RBP operation modes, such as the back flow or the ventricular collapse during the cardiac cycle [24].

For example, several algorithms for detecting the ventricular collapse onset using a hydrodynamic system have been tested in [25]. These algorithms can be implemented in the RBP control system.

A system for detecting the ventricular collapse onset was described in [26]. This system distinguishes between three pumping states: normal pump operation, approach of ventricular collapse, operation in the ventricular collapse mode. It uses the Lagrangian support vector technique, which combines six indices based on the time diagram of flow through the pump. The system was tested using the results of *in vivo* tests of two rotary blood pumps. Indices for detecting the ventricular collapse from the pump speed diagram were suggested in [24]. The sensitivity of the indices was 98.9%; the specificity, 99.7%.

The system for detecting the aortic valve (AV) closure suggested in [27] is based on the integral dependence of the pump input pressure on the pump power per single cardiac cycle. The dependence was obtained using animal testing data. It was demonstrated that the estimated dependence of the input pressure on the pump power reached its maximum when the pump speed variation led to complete closure of the aortic valve. The authors believe that the obtained data can be used as an experimental basis for the development of an automatic controller.

A similar goal – estimation of the AV state during RBP operation – was pursued in [28-34]. Thus, clinical implementation of this function can be considered as an important task. In particular, it can be used to implement control strategies for restoration of the myocardium.

A new method for determination of physiologically significant modes of RBP operation was suggested in [3]. The method was based on a dynamic RBP model. Later this method was modified and tested using a mathematical model of the cardiovascular system. The goal of the test was to check the ability of the RBP to provide the required capacity level [36]. It was shown that the method allowed the required capacity level to be attained. It also allowed prevention of undesirable states of the cardiovascular system caused by various physiological changes.

Physiological Control Systems

The main goal of physiological control systems is to provide the physiological mode of blood circulation, i.e., the optimal RBP capacity. An example of such system was described in [37], where a universal technique for the centrifugal or axial RBP control was suggested. This technique was intended to provide the physiological mode of the RBP operation by maintaining a fixed pressure difference between the left ventricle and the aorta. An algorithm for the prevention of ventricular collapse by maintaining the differential speed of the pump above a given threshold level was also suggested in [37]. The control system was tested using a model of the cardiovascular system at rest and during physical exercise. We suggest measuring the pressure difference using pressure sensors. A similar algorithm for physiological circulation support was reported in [38]. The main idea of the algorithm was to support the mean aortic pressure at the level 100 mm Hg and to increase the pulsation pressure to 20 mm Hg. For this purpose, the pump speed was modulated using the indices derived from the aortic pressure diagram. These indices were used to determine the amplitude and to synchronize the speed modulation with the cardiac cycle. The algorithm suggested in this work was tested *in vitro* and in a model of the cardiovascular system.

A method for determination of the pump speed profiles was suggested in [39]. This method optimized the VAD interaction with the cardiovascular system and made it possible to develop a personal strategy of VAD control. It was based on a mathematical model of the cardiovascular system and the RBP. The speed profiles synchronized with the cardiac cycle obtained by this method were found to be optimal for maximizing the blood flow through the aortic valve and minimizing the impact work. A method of physiological control similar to the Starling mechanism was reported in [40-42]. The required value of the flow through the pump was estimated using the linear ratio between the mean flow Q_{VAD} and the flow pulsation $Q_{VAD,\ PULS}$. This ratio was derived from the dependence of the pump flow on the end-diastolic pressure in the left ventricle with substitution of $Q_{VAD,\ PULS}$ instead of P_{LVED}. The obtained dependence was found to be similar to the Starling curve.

At the end of each time step t, after measuring or estimating $Q_{VAD,\ t}$ and $Q_{VAD,\ PULS,\ t}$, a new position of the point OP_t relative to the control line CL_n is determined (Fig. 1). If the state of the cardiovascular system changes, the working point deviates from the control line. A new value of the mean flow through the pump is estimated at the next moment $Q_{VAD,\ t+1}$ to bring the $Q_{VAD,\ PULS,\ t}$ to a new working point OP_{t+1} in the control line CL_n. This procedure is described by the following equation:

$$Q_{VAD,\,t+1} = \left[\sqrt{\left(Q_{VAD,\,t}\right)^2 + \left(Q_{VAD,\,PULS,\,t}\right)^2}\right]\sin\theta_n,$$

where $Q_{VAD,\ t+1}$ is the required flow through the pump; $Q_{VAD,\ t}$ is the mean pump capacity; $Q_{VAD,\ PULS,\ t}$ is the pump flow pulsation; θ_n is the slope angle of the control line CL_n.

The method based on selection of the flow pulsation through the pump is considered to be optimal for stable control of blood circulation using the controller described in [43]. This method was tested using a model simulating the state of the cardiovascular system under conditions of physical exercise and sudden blood loss. The similarity with the Starling mechanism, which describes the biological heart reaction to changes in preload, makes it possible to prevent the scenarios of excessive or insufficient evacuation of blood from the ventricle.

Several controller models for physiological control of VAD based on similar principles are described in [44, 45]. For example, in [45] it was suggested to regulate the pump speed and, as a sequence, the pump capacity according to the end-diastolic volume of the left ventricle. This controller was tested using a hydrodynamic system with given left ventricular volume; thus, the problem

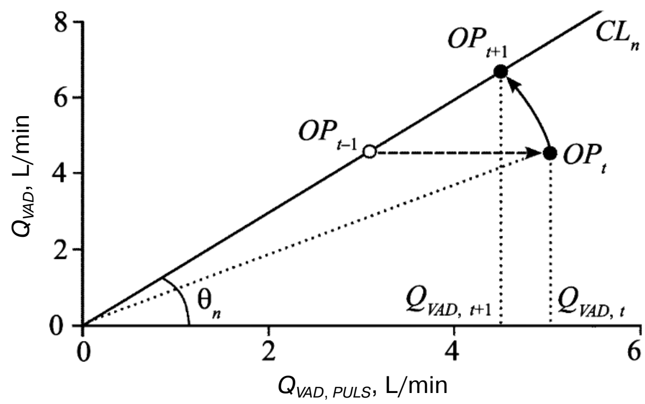

Fig. 1. Selection of a new working point on the control line CL_n in the case of changes in the state of the cardiovascular system [43].

of the volume measurement was not discussed in this work. The results of the study showed the controller to be highly sensitive to the preload. It allowed fast regulation of the pump speed and made it possible to prevent the scenarios of excessive or insufficient evacuation of blood from the ventricle. Later, a method of calibration of similar controllers sensitive to the preload was developed [46]. This method was tested using a numerical model of blood circulation.

It was demonstrated in hydrodynamic tests [47] that physiological control systems using the end-diastolic pressure of the left ventricle as preload were especially effective for the prevention of ventricular collapse.

Conclusion

A review of control algorithms, methods, and systems for ventricular assist devices is presented. Special attention is paid to their capacity and advantages for treatment of cardiac insufficiency. VAD control systems used in current clinical practice are described.

It can be noted that evaluation of the aortic valve state during the RBP operation is the most-in-demand function of the control systems. This function is important for conservation of the functional activity of the aortic valve, restoration of the activity of the myocardium, and development of new strategies of therapy of patients with moderate cardiac insufficiency.

Control systems for biventricular assist devices were not considered in this work. The disadvantages of the control systems requiring pressure measurement in the left ventricle or the aorta can be overcome using noninvasive estimation techniques similar to that reported in [48].

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