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Continuous Cardiac Output Estimation Under Left Ventricular Assistance

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Abstract: Sufficient cardiac output is the main goal of ventricular assist device therapy. To date, there is no adequate method to estimate the combined amount of blood the heart and an continuous-flow assist device pump through the circulatory system. This paper presents an approach to estimate the cardiac output based on the signals provided by optical pressure sensors mounted on the inlet and outlet of an Impella CP pump. An extended Kalman filter for joint estimation of the aortic flow rate and the hydraulic resistance of the aortic valve is introduced. It uses a third order nonlinear state-space model of the aortic valve, aortic arch and systemic circulation with six parameters. The accuracy of the estimated cardiac output is investigated in an animal study with two sheep suffering from acute ischemic heart disease supported by a left ventricular assist device. The extended Kalman filter with joint parameter and state estimation yields an error of $0.47 \pm 0.32\,\mathrm{L} \cdot \mathrm{min}^{-1}$. It is compared to an extended Kalman filter without parameter identification which achieves a comparable error of $0.49 \pm 0.26\,\mathrm{L} \cdot \mathrm{min}^{-1}$. The errors are in the same order of magnitude as the accuracy of the clinical gold standard for invasive blood flow diagnostics. The introduced method enables cardiac output to be used as the control variable of a physiological control strategy for closed-loop ventricular assist device therapy.

Keywords: Biomedical systems, Estimators, Extended Kalman filters, Lumped-parameter systems, Parameter estimation, State estimation, State-space models

1. INTRODUCTION

Low cardiac output (CO) due to various heart diseases is one of the main indications for ventricular assist device (VAD) therapy. CO is the combined amount of blood the heart and an assist device pump through the circulatory system per minute. A VAD is thereby used to provide adequate CO when the heart failure is resistant to pharmaceutical therapy, see Wilson et al. (2009) and Slaughter et al. (2009). The recent INTERMACS report by Kirklin et al. (2014) shows that continuous-flow pumps gradually replace pulsatile devices. Although increasing CO is a primary goal of VAD therapy, few researchers have addressed the real time measurement or estimation of CO under continuous-flow left ventricular assistance. This paper proposes model based methods to estimate the aortic flow rate during VAD therapy. The VAD used in this study is a percutaneous, catheter-based device that is positioned across the aortic valve (AV). It pulls blood from the left ventricle (LV) and expels it into the ascending aorta. Most clinical standard methods for CO measurement as described by De Waal et al. (2009) and Mehta and Arora (2014) cannot be used, as the total flow is a combination of the residual native heart function and the VAD output.

Existing CO estimation techniques can be subdivided in instrumentation and model based approaches. The former focus on adapting standard methods in order to use them during VAD therapy. Raman et al. (2009) used the indicator dilution principle to estimate aortic blood flow from computed tomography images; the results are reasonable with an average underestimation of $0.54 \pm 0.37\,\mathrm{L} \cdot \mathrm{min}^{-1}$. The main limitation of this method, besides the radiation exposure, is the manual selection of the region of interest, which cannot be done in real time. Scolletta et al. (2011) evaluated an uncalibrated pulse contour method to monitor CO in patients supported with a pulsatile left VAD. They achieved an average overestimation of $0.04 \pm 0.38\,\mathrm{L} \cdot \mathrm{min}^{-1}$ compared to pulmonary thermodilution; the main shortfall is the dependence on the existence of a pulse contour. Hence, the uncalibrated pulse contour method is not applicable in patients supported by an continuous-flow VAD without major modifications.

Model based CO estimation methods rely on standard measurements taken during VAD therapy. The cardiovascular system combined with a VAD is modeled as three or four-element Windkessels as introduced by Frank (1899) combined with nonlinear elements such as valves, time-varying compliances and friction elements. The CO is usually a state of this model that is observed or estimated. Yoshizawa et al. (1993) were among the first to apply this method to left VAD support in counter pulsation mode. They identified the parameters of a simple electrical circuit model (with five components) of the circulatory system and used a steady state Kalman filter to estimate the CO.

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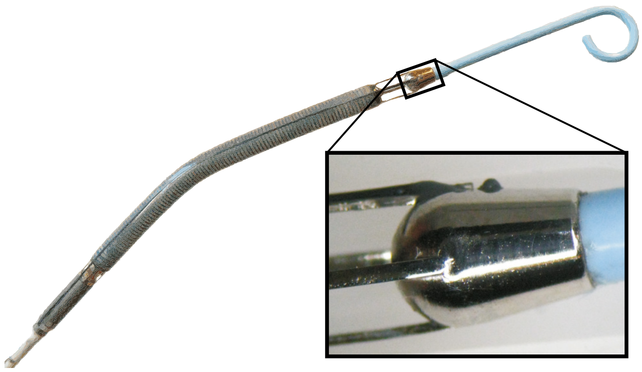

Fig. 1. Modified Impella CP with fiber optical pressure sensors; the detailed picture shows the mounting of the sensor at the inlet cannula.

The main limitation of the method proposed by Yoshizawa and co-workers is that it cannot be applied when the outflow from the natural heart and the VAD overlap in time. Thus, it is not possible to estimate flow rates during continuous-flow VAD support with this method. Various approaches have been suggested to analyze the waveform of the arterial blood pressure in order to estimate the aortic blood flow, see Mukkamala et al. (2006) and Arai et al. (2012). Unfortunately, these methods have never been investigated during VAD therapy. There is a considerable amount of methods for estimating the blood flow through the VAD, see Funakubo et al. (2002), Ayre et al. (2003), and Malagutti et al. (2007). However, none of these methods have been extended to the estimation of CO.

The electrical circuit model of the cardiovascular system suggested by Simaan et al. (2009) seems to be useful for estimating physiologically meaningful states. They introduced a sixth-order, nonlinear set of differential equations in which one of the states is the cardiac output. Simaan and co-workers were not able to estimate the states of this model, as the only available state for measurement in their study was the pump flow. This paper investigates a third order model in combination with more measurements to estimate the CO under left ventricular assistance in real time. We present two parallel (extended) Kalman filters that use measurements of optical pressure sensors on the pump inlet and outlet as well as the pump flow to derive the aortic flow rate and the hydraulic resistance of the AV.

The proposed CO estimator is evaluated in an animal study with two sheep suffering from acute ischemic heart disease supported by a left VAD. The CO estimation results are compared to a reference measured with a perivascular ultrasonic flow probe at the pulmonary artery. The parallel (extended) Kalman filter approach with parameter identification yields an estimation error of $0.47 \pm 0.32\,\mathrm{L}\cdot\mathrm{min}^{-1}$. The proposed filter structure is compared to an extended Kalman filter without joint parameter estimation which achieves an error of $0.49 \pm 0.26\,\mathrm{L}\cdot\mathrm{min}^{-1}$.

The paper is structured as follows. Section 2 describes the left VAD used in this study and introduces the corresponding cardiovascular system model. Section 3 presents the parallel (extended) Kalman filter structure for CO estimation; in vivo results are presented in Section 4. Finally, the results are discussed in Section 5 and conclusions are drawn in Section 6.

2. ASSIST DEVICE AND CARDIOVASCULAR SYSTEM MODEL

The VAD utilized in this study is an Impella CP (ABIOMED Inc., Danvers, USA), a miniaturized percutaneously inserted turbodynamic pump that transports blood from the LV into the ascending aorta at an upper rate of $4\,\mathrm{L}\cdot\mathrm{min}^{-1}$. It potentially enables immediate and sustained unloading of the LV while increasing the overall systemic cardiac output; see Mukku et al. (2012) for a study with a previous version of this pump. We use a modified pump augmented with two fiber optical sensors mounted at the inlet and outlet cannulae as depicted in Fig. 1. The sensor technology was introduced by Abeysinghe et al. (2001) and enables the measurement of the left ventricular pressure p_{LV} and the aortic pressure p_{A} with high precision. Optical measurements have several advantages over pressure acquisition with fluid-filled catheters. There is virtually no delay due to pulse transit time and no peak pressure overestimation due to the inertia of the fluid, see De Vecchi et al. (2014). Therefore, the waveform shape of the pressure signals is preserved, which is an important prerequisite for the model based estimation of the CO.

The design of the cardiovascular system model depicted in Fig. 2 was geared towards simplicity. Having a pressure sensor in the LV allows us to neglect the hydraulic properties of the ventricle and model it as a voltage source in the electrical model. The AV is included as an ideal

Table 1. Variables of the cardiovascular system model.

Variable	Quantity/Interpretation	Unit
p_{A}	Aortic pressure	mmHg
p_{S}	Systemic pressure	mmHg
p_{LV}	Left ventricular pressure	mmHg
q_{A}	Aortic flow rate	$\mathrm{mL}\cdot\mathrm{s}^{-1}$
q_{VAD}	VAD flow rate	$\mathrm{L}\cdot\mathrm{min}^{-1}$

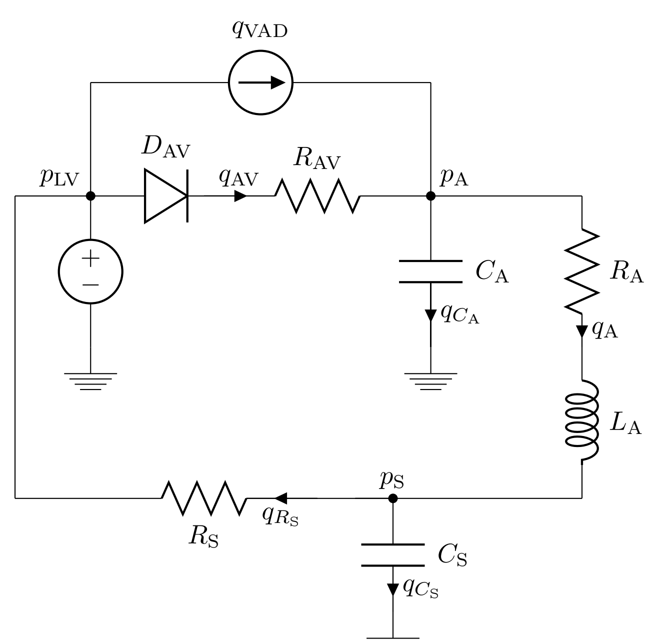

Fig. 2. Simple electrical model of the aortic valve, the aortic arch and the systemic circulation.