# Improving the Pulsatility in a CF-LVAD Supported Cardiovascular System Applying a Model Control to CF-LVAD Flow Rate

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## Introduction

Continuous Flow Left Ventricular Assist Devices (CF-LVADs) reduce the pulsatility in the cardiovascular system while supporting the failing heart. It has been reported that enhanced pulsatility has significant benefits on vital organ function in the patients [1]. In this study, the operating speed of a CF-LVAD was regulated to control the flow rate through the CF-LVAD, to improve the pulsatility and the shape of the systemic arterial pressure signal over a cardiac cycle.

## Materials and Methods

To simulate the healthy and dilated cardiomyopathic (DCM) heart in a combination with the circulatory system a model was developed considering the analogy between electrical and hemodynamical systems [2]. The complete cardiovascular system model consists of the heart chambers and heart valves, systemic arteries and veins and pulmonary arteries and veins. The model of the ventricles describes the ventricular wall mechanics, myocardial constitutive properties and intramyocardial pressure [3,4]. The heart rate in the CVS model was modulated using a baroreflex model [5]. To simulate LVAD support, a model which estimates the pressure difference across the Micromed DeBakey CF-LVAD considering the operating speed of the pump, flow rate and change of the flow rate through the pump [6] was integrated into the cardiovascular system model. In the simulations of the assisted cardiovascular system, the operating speed of the CF-LVAD was regulated applying proportional-integral control to flow rate through the CF-LVAD. The reference flow rate was obtained from a model which describes the dynamics of a healthy left ventricle and systemic arteries. This model is given below (Eq. 1-3). The electric-analogue of the assisted cardiovascular system model and block diagram of the control application are given in Figure1.

$$dp_{as,m}/dt = ((p_{lv,m} - p_{as,m})/R_{av,m} - (p_{as,m} - (V_{tot,m} - V_{u,m} - V_{lv,m} - p_{as,m}C_{as,m})\,/C_{la,m})/R_{as,m})/C_{as,m} \quad (1)$$
$$Q_{as,m} = (p_{as,m} - (V_{tot,m} - V_{u,m} - V_{lv,m} - p_{as,m}C_{as,m})\,/C_{la,m})/R_{as,m} \quad (2)$$
$$Q_{ref} = K_1 dP_{as,m}/dt + K_2 Q_{as,m} \quad (3)$$

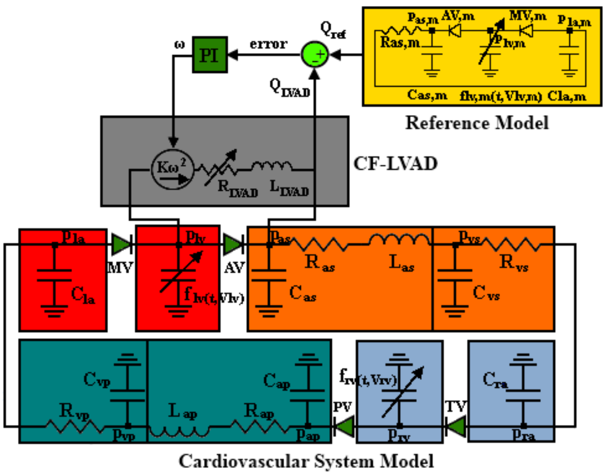


Figure 1. Electric-analogue of CF-LVAD integrated cardiovascular system model and block diagram of control application

*dp/dt* is the change of pressure with respect to time, *p* is pressure, *V* is volume *Q* is flow rate, *R* is resistance and *C* is compliance in the equations above. The subscripts *as*, *lv*, *av*, *la*, *tot*, refer to systemic arteries, left ventricle, aortic valve, left atrium, total respectively. u denotes unstressed blood volume. Subscripts ref and m denote reference and model parameters. $K_1$ and $K_2$ are the coefficients in the equation describing the reference CF-LVAD flow. *AV*, *MV*, *TV* and *PV* denote aortic, mitral tricuspid and pulmonary valves respectively. L denotes inertance and f denotes ventricle models. The subscripts *vs*, *ra*, *rv*, *ap* and *vp* denote systemic veins, right atrium,

right ventricle, pulmonary arteries and veins respectively. Finally, *t* denotes instantaneous time in Figure 1.
In the varying speed CF-LVAD operating application the highest and lowest speeds were set to 16000 rpm and 4000 rpm respectively. To make an accurate comparison between pulsatility of the vascular haemodynamics in the varying speed regulated CF-LVAD assistance and constant speed CF-LVAD assistance mean pump output (MPO) of the regulated CF-LVAD was calculated. The same MPO was obtained approximately at 11160 rpm speed in constant speed CF-LVAD assistance. Body surface area of the patient was assumed to be 1.9 $m^2$ to enable the calculation of cardiac index (CI). Simulations were performed using Matlab Simulink with the ode15s solver. Maximum step size was 0.0005 s.

## Results and Discussion

Simulations were performed for healthy and DCM cardiovascular system models without assistance first. LV, RV, systemic and pulmonary arterial pressures, LV and RV volumes, cardiac outputs and heart rates for healthy and DCM cardiovascular systems are in summarized in Table 2.

Table 1. Hemodynamic variables for healthy and DCM models

| | $p_{lv}$[mmHg] | $p_{as}$[mmHg] | $p_{rv}$[mmHg] | $p_{ap}$[mmHg] | $V_{lv}$[mL] | $V_{rv}$[mL] | CO[mL/min] | HR[bpm] |
|---|---|---|---|---|---|---|---|---|
| Healthy | 5-123 | 84-122 | 1-29 | 16-29 | 49-125 | 37-113 | 5548 | 73 |
| DCM | 33-82 | 60-80 | 1-49 | 40-48 | 227-269 | 42-84 | 3906 | 93 |

As indicated in Table 1, systolic pressure in the left ventricle and systemic arteries decreased significantly. In DCM diastolic pressure in left ventricle increased. Systolic pressure in right ventricle and pulmonary arteries increased. Left ventricular volume increased over a cardiac cycle, however, stroke volume in both ventricles decreased. Cardiac output decreased and heart rate increased in DCM condition. So the model is capable of describing the circulatory dynamics of an LVAD implantation candidate.
The model results with CF-LVAD incorporated for mean arterial pressure, pulse pressure in systemic arteries, cardiac output and mean pump output, end systolic and end diastolic volumes heart rates and cardiac index for the healthy model, DCM model, varying CF-LVAD operating speed application and constant CF-LVAD operating speed application are given in Figure 2.

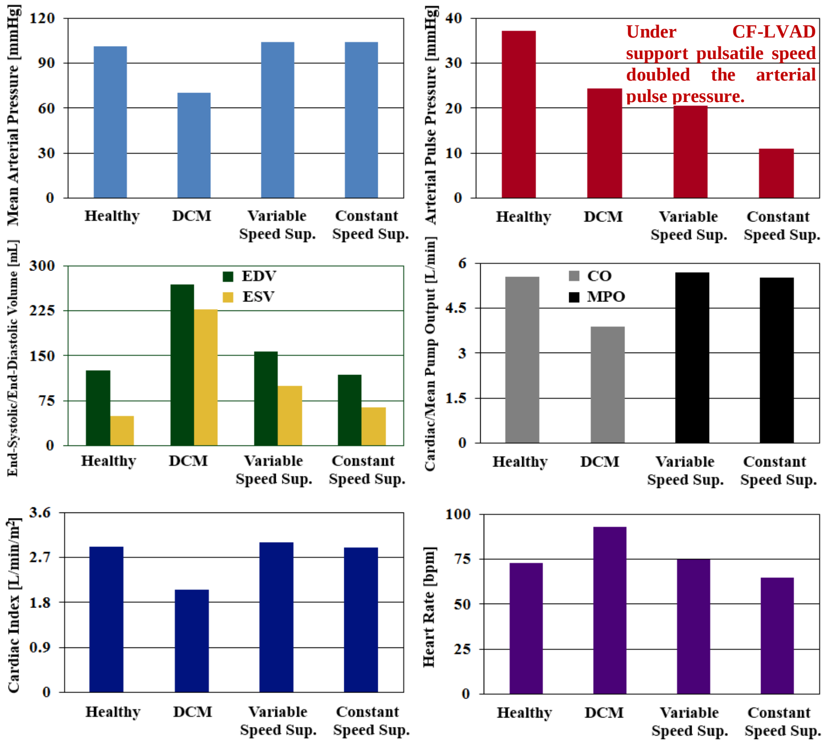

Figure 2. Comparison of the hemodynamic variables in healthy and DCM models, varying and constant speed CF-LVAD support

As shown in Figure 2, varying speed CF-LVAD support and constant speed CF-LVAD support increases the mean arterial pressure in healthy state. However, pulse pressure in varying speed CF-LVAD support was almost two times higher than in constant speed CF-LVAD support. The LV volume in DCM model decreased in both varying and constant speed CF-LVAD support. Both varying and constant speed CF-LVAD support provided more than 5L/min mean output. So, the cardiac

index was at the healthy level for both operating modes. Decreased arterial pressure caused the increase in heart rate in the DCM model. In both operating modes heart rate decreased to a healthy level again. As mentioned before arterial pulse pressure doubled under the pulsatile speed CF-LVAD support.
In future studies, the method will be validated experimentally.

## Conclusion

Simulation results showed that applying a pulsatile pump speed to the CF-LVAD, provides sufficient support to a DCM cardiovascular system model. Also varying speed over a cardiac cycle increases the pulse pressure and may reduce the long term complications associated with CF-LVAD support.


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