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Mathematical analysis of the effects of valvular regurgitation on the pumping efficacy of continuous and pulsatile left ventricular assist devices

Yoo Seok Kim[a,1], Eun-Hye Kim[a,1], Hyeong-Gyun Kim[b], Eun Bo Shim[c], Kwang-Soup Song[a], Ki Moo Lim[a,*]

[a] Department of Medical IT Convergence Engineering, Kumoh National Institute of Technology, Gumi, Korea
[b] Department of Radiological Science, Far East University, Eumseong, Korea
[c] Department of Mechanical and Biomedical Engineering, Kangwon National University, Chuncheon, Korea

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ABSTRACT

Background: A left ventricular assist device (LVAD) is normally contraindicated in significant aortic regurgitation (AR) and requires intraoperative valve repair or exclusion. Nevertheless, AR can coexist with an LVAD, so a valid question when asked might still be of clinical significance. The purpose of this study is to analyze the effects of valve regurgitation on the pumping efficacy of continuous and pulsatile LVADs with a computational method.
Methods: A cardiovascular model was developed based on the Windkessel model, which reflects the hemodynamic flow resistance and the blood wall elasticity. Using the Windkessel model, important cardiovascular components, such as the right atrium, right ventricle, pulmonary artery, pulmonary vein, left atrium (LA), left ventricle (LV), aorta, and branching blood vessels, were expressed.
Results: In the case of AR, continuous and pulsatile LVADs improved cardiac output and reduced mechanical load slightly. In the case of mitral regurgitation, the LVADs improved cardiac output (cardiac outputs were about 5 L/min regardless of the severity of regurgitation) and reduced afterload significantly.
Conclusion: AR reduced both continuous and pulsatile LVAD function significantly while mitral regurgitation did not affect their pumping efficacy.

* *Corresponding author.* Department of Medical IT Convergence Engineering, Kumoh National Institute of Technology, Yangho-dong, Gumi, Gyeongbuk 730-701, Korea.
E-mail address: kmlim@kumoh.ac.kr (K.M. Lim).
[1] Yoo Seok Kim and Eun-Hye Kim contributed equally to this work.
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1. Introduction

A left ventricular assist device (LVAD) is an electromechanical device used to replace part of the function of a failed heart, by helping to circulate blood through the body. Recently, LVADs have been used as a bridge to transplantation[1] or destination therapy.[2,3] Valve regurgitation, i.e., backward flow in the heart when a cardiac valve does not completely close, has been found to have a significant effect on cardiac function.[4] Heart valves are located between the atria and the ventricles (the mitral and tricuspid valves), and between the ventricles and the aortas (the aortic and pulmonary aortic valves). Cardiac responses, such as cardiac output and blood pressure, vary according to which valve is affected and the severity of regurgitation. Valve regurgitation also affects the LVAD pumping efficacy differently following LVAD therapy.[5,6] LVAD is normally contraindicated in significant aortic regurgitation (AR) and requires intraoperative valve repair or exclusion.[7,8] Furthermore, LVAD aggravates preexisting AR.[9,10] Nevertheless, AR can coexist with LVAD,[11] so a valid question when asked might still be of clinical significance.

While much research has focused on determining regurgitation volume using medical imaging techniques, and also predicting the effects of regurgitant volume on ventricular mechanical function,[12,13] no study has focused on predicting the effects of regurgitation severity in specific valvular regurgitation on LVAD function in the failed ventricle following LVAD therapy.

The pumping efficacy of LVADs according to the severity of valvular insufficiency can be investigated in animal and clinical studies. However, experimental methods to document and evaluate cardiac responses in detail, such as the ventricular unloading effect of LVAD, are hampered by low spatiotemporal resolution. As an alternative, computational methods can be applied. We have performed several studies comparing ventricular unloading effects under different pumping types[14,15] and cannulation sites[16] using computational methods.

We used a previously developed computational model of the cardiovascular system to analyze the effects of aortic and mitral valve regurgitation on the pumping efficacy of continuous and pulsatile LVADs.

2. Methods

2.1. *Cardiovascular model*

As shown in Fig. 1, the cardiovascular model was developed based on the Windkessel model, which reflects the hemodynamic flow resistance and the blood wall elasticity.[17] Dynamic parameters, such as flow resistance and blood wall elasticity, were expressed as the electric resistance and the electric compliance components, which are linear electric circuit elements. Using the Windkessel model, important cardiovascular components, such as the right atrium, right ventricle, pulmonary artery, pulmonary vein, left atrium (LA), left ventricle (LV), aorta, and branching blood vessels, were expressed.

The heart spontaneously contracts and relaxes repeatedly through electrical signals, action potentials, to change its elasticity, which is a dynamic material property. Considering these features, the time-varying compliance suggested by Suga and Sagawa[17] was used in this study, unlike other linear capacitors (Fig. 2). The LVAD was assumed to be a flow generator that continuously ejects blood, and was connected in parallel to the LV and the aorta, as shown in Fig. 1. The cardiovascular model is composed of eight Windkessel compartments, each of which is expressed as Eq. (1), Eq. (2), and

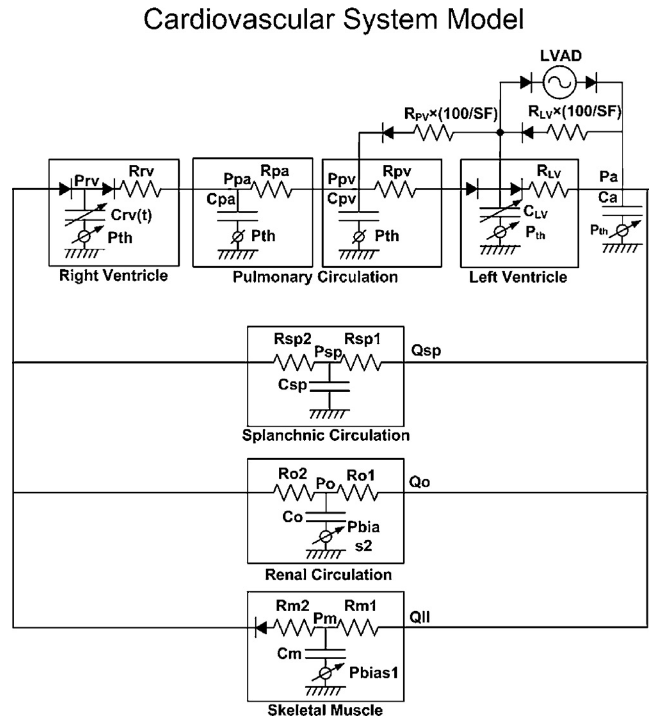

Fig. 1 – Schematic drawing of the cardiovascular system model that consists of eight compartments. See Lim et al[15] for the detailed parameter information.
SF, scale factor for the leakage resistance.

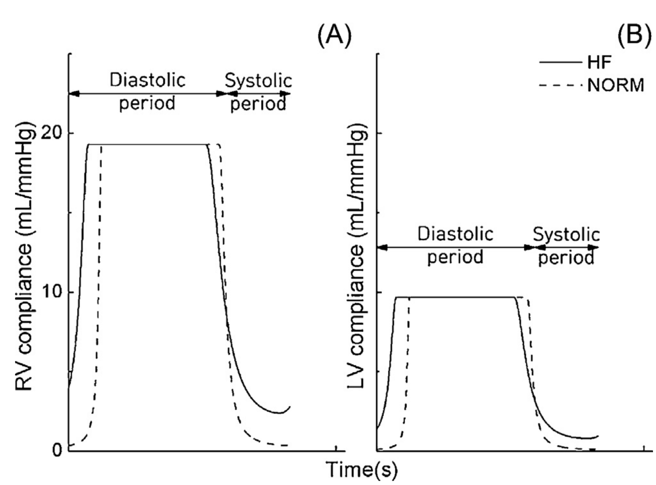

Fig. 2 – Time-varying compliance of the right and left ventricles.
HF, heart failure; NORM, normal condition.