

## The effect of left ventricle unloading by the Jarvik 2000 assist device on coronary blood flow

*Jarvik 2000 destek cihazı ile sol ventrikül yükünün azaltılmasının koroner kan akımı üzerine etkisi*

**Egemen Tüzün, Kanber Öcal Karabay, Jeff Conger, Howard Frazier, Kamuran Kadıpaşaoğlu**

Cardiovascular Surgery Labs, Texas Heart Institute, Houston/TX, USA

**Background:** The purpose of this study was to evaluate the effects of left ventricle unloading by the Jarvik 2000 axial-flow pump on coronary blood flow.

**Methods:** The Jarvik 2000 pump was implanted in 10 calves using partial cardiopulmonary bypass. Left ventricular (LV) hemodynamics, coronary blood flow (CBF), and myocardial oxygen consumption (MVO<sub>2</sub>) were measured when the pump was operating at 8,000, 10,000 and 12,000 rpm, and the results were compared with the baseline (pump off, 0 rpm) values. Echocardiography was performed at increasing speeds to evaluate left and right ventricular dimensions and aortic valve opening.

**Results:** No surgical or device-related complications occurred. The Jarvik 2000 significantly increased the mean and diastolic aortic pressures and resulted in narrowed pulse pressure at speeds above 10,000 rpm ( $p<0.05$ ). Left ventricular end-systolic and end-diastolic pressures, pulmonary capillary wedge pressure, and LV dimensions gradually decreased at higher pump speeds. Although coronary blood flow and myocardial oxygen consumption decreased at increasing pump speeds ( $p<0.05$ ), the ratio of CBF to MVO<sub>2</sub> remained between 0.18 and 0.20 in all calves throughout the study. Right heart pressures were not affected by increases in pump speeds and remained close to the baseline values.

**Conclusion:** We conclude that left ventricle unloading with Jarvik 2000 pump does not compromise LV functions and affect CBF/MVO<sub>2</sub> ratio.

**Key words:** Blood flow velocity; blood pressure; coronary circulation; echocardiography; heart-assist devices; heart failure, congestive; myocardium; oxygen consumption; prosthesis implantation; vascular resistance; ventricular function, left.

**Amaç:** Bu çalışmada, sol ventrikül yükünün Jarvik 2000 aksiyal akım pompası ile azaltılmasının koroner kan akımı üzerine etkileri değerlendirildi.

**Çalışma planı:** Jarvik 2000 pompası parsiyel kardiyopulmoner bypass yöntemi kullanılarak 10 adet buzağıya implante edildi. Pompa 8000, 10000 ve 12000 devir/dakika hızlarda çalıştırılırken sol ventrikül (LV) hemodinamik değerleri, koroner kan akımı (CBF) ve miyokard oksijen tüketimi (MVO<sub>2</sub>) ölçüldü ve bu değerler bazal değerler (pompa hızı 0 devir/dakika) ile karşılaştırıldı. Artan hızlarda sağ ve sol ventrikül boyutları ve aort kapak açıklığı ekokardiyografi ile ölçüldü.

**Bulgular:** Cerrahi işlem ya da pompayla ilgili herhangi bir komplikasyon gelişmedi. Jarvik 2000 pompasının artan hızlarında ortalama ve diyastolik aortik basınçlar anlamlı olarak yükselirken, 10000 devir/dakikanın üzerindeki hızlarda nabız basıncı azaldı ( $p<0.05$ ). Artan pompa hızlarında LV sistol ve diyastol sonu basınçları, pulmoner kapiller uç basıncı ve LV boyutları dereceli olarak azaldı. Her ne kadar artan hızlarda koroner kan akımı ve miyokard oksijen tüketimi azaldıysa da ( $p<0.05$ ), CBF'nin MVO<sub>2</sub>'ye oranı çalışma boyunca tüm deneklerde 0.18 ile 0.20 arasında kaldı. Sağ kalp basınçları pompa hızındaki artışlardan etkilenmedi ve başlangıç değerlerine yakın seyretti.

**Sonuç:** Çalışmamızda, sol ventrikül yükünün Jarvik 2000 pompası ile azaltılması sırasında LV işlevleri ve CBF/MVO<sub>2</sub> oranı olumsuz olarak etkilenmedi.

**Anahtar sözcükler:** Kan akım hızı; kan basıncı; koroner dolaşım; ekokardiyografi; kalp destek cihazı; kalp yetersizliği, konjestif; miyokard; oksijen tüketimi; protez implantasyonu; ventrikül fonksiyonu, sol.

Received: July 12, 2004 Accepted: August 9, 2004

Correspondence: Egemen Tüzün, MD, Texas Heart Institute, Cardiovascular Surgery Labs, 6770 Bertner Avenue MC 1-268 Houston, TX 77030, USA. Tel: +1 832 355 73 19 e-mail: etuzun@heart.thi.tmc.edu

Left ventricular assist devices (LVAD), either pulsatile or non-pulsatile, are currently used as “bridge to transplantation,”<sup>[1]</sup> “bridge to recovery”<sup>[2]</sup> or “destination therapy”<sup>[3]</sup> in patients with end-stage heart failure refractory to conventional medical and surgical treatments. However, despite the advances in LVAD development, acute and chronic end-organ effects of these devices are still unclear and controversial.

The Jarvik 2000 is an intraventricular, small sized and easily implantable axial-flow LVAD (Jarvik Heart, Inc., New York, NY), which reduces inlet graft kinking, stagnation, thrombosis, and risk of infection.<sup>[3]</sup> In this acute experimental study, we assessed the effects of left ventricle unloading by Jarvik 2000 LVAD on LV coronary blood flow and functions in a nonischemic bovine model.

## MATERIALS AND METHODS

**Jarvik 2000 axial flow pump.** The Jarvik 2000 LVAD is an electrically powered, axial-flow impeller pump that consists of a blood pump, 16-outflow graft, a percutaneous power cable, a pump-speed controller, and an external direct-current power supply. Its design was previously described in detail.<sup>[4]</sup>

**Animal model.** Experiments were conducted on 10 Corriente crossbred calves, each weighing between 97-114 kg. All the calves received humane care in compliance with the Principles of Laboratory Animal Care (National Society of Medical Research) and the Guide for the Care and Use of Laboratory Animals (National Institutes of Health, publication no. 85-23, revised 1996). Our institution’s Institutional Animal Care and Use Committee approved all protocols used in the present study.

**Anesthesia and surgical preparation.** A standard anesthesia protocol was followed. Each calf was premedicated with glycopyrrolate (0.02 mg/kg) and xylazine (0.2-0.7 mg/kg) both given intramuscularly. Anesthesia was induced with intravenous ketamine (10-20 mg/kg). A cuffed endotracheal tube and an orogastric decompression tube were inserted. General anesthesia was maintained with isoflurane (1.0-3.0%) in oxygen (40-100%). The anesthetized calf was then placed on the operating table in the right lateral decubitus position in preparation for a left thoracotomy and left neck cutdown. Electrocardiographic leads were connected, and a rectal temperature probe was inserted.

**Surgical technique.** A detailed description of the surgical implantation procedure was published previously.<sup>[5]</sup> Briefly, a left thoracotomy was performed in the fifth intercostal space and the fifth rib was removed. An arterial pressure catheter was placed into the left internal thoracic artery. The left carotid artery and left

jugular vein were exposed for cardiopulmonary bypass (CPB) cannulation. After heparinization (3 mg/kg), a 16-mm Dacron outflow graft was anastomosed to the descending thoracic aorta in end-to-side fashion with a 4-0 propylene suture using a partially occluding vascular clamp. After partial CPB was initiated, a silicone/polyester sewing cuff was sewn to the ventricular apex with pledgeted, coated, braided 2-0 polyester mattress sutures. The LV apex was cored with a circular knife on the beating heart. The FlowMaker was inserted into the LV apex and secured with cotton tapes and tie band(s) around the cuff. After the pump was secured, the outflow graft was connected to the pump outflow and was secured with two cotton tapes. The pump and the graft was de-aired using an 18 gauge needle and then the needle hole was repaired with 5/0 prolene suture. A 16-mm ultrasonic flow probe (Transonics Inc., Ithaca, NY) was placed on the outflow graft. The calf was then slowly weaned from CPB.

**Intraoperative hemodynamic data collection.** Once surgery was completed, a high-fidelity micromanometer tip (Millar Micro-Tip Catheter; Millar Instruments, Houston, TX) pressure catheter was inserted into the LV via the left carotid artery for continuous LV pressure measurements. An 8F Swan-Ganz catheter was inserted into the pulmonary artery via the left external jugular vein for continuous right heart pressure monitoring. A pressure catheter was inserted via the left internal thoracic artery to measure continuous arterial pressure. Two ultrasonic flow probes (Transonics Inc., Ithaca, NY) were then placed on the pump’s outflow graft (16-mm flow probe) and the proximal left anterior descending coronary artery (3-mm flow probe). Data were recorded by a 16-channel computer data acquisition system (Ponemah System version 3.3; Gould Instrument Systems Inc., Valley View, OH).

Data were collected for 20 minutes at each of several pump settings in sequence: first with the pump off and the outflow graft clamped to avoid pump regurgitation (0 rpm) (baseline) and then stepwise with the pump operating at various increasing speeds (8,000, 10,000, and 12,000 rpm). At each speed, the pump was allowed to operate for 10 minutes to allow cardiac recovery before data collection began. The data that were gathered included mean heart rate (HR), systolic pressure (AoPs), diastolic pressure (AoPd), mean aortic (AoPm) pressure, mean pulmonary artery pressure (PAP), pulmonary capillary wedge pressure (PCWP), central venous pressure (CVP), LV systolic pressure (LVP), LV end-diastolic pressure (LVEDP), pump outflow graft flow (PF), and coronary blood flow (CBF). At study termination, animals were fully heparinized (3 mg/kg) and euthanized.

**Table 1. Hemodynamic and echocardiographic measurements of the left and right heart**

	Pump speed (rpm)			
	Pump off (Baseline)	8,000	10,000	12,000
Heart rate (bpm)	79±13	81±15	80±20	78±14
Aortic pressure (mmHg)				
Systolic	87±15	90±15	88±13	89±11
Diastolic	63±10	67±8	74±9*	77±13*
Mean	75±12	78±11	81±11*	81±14*
Left ventricular systolic pressure (LVP) (mmHg)	89±10	85±8	78±13	49±24*
Left ventricular end-diastolic pressure (mmHg)	12±4	11±3	8±4*	6±5*
Pulmonary capillary wedge pressure (mmHg)	12±2	12±2	10±4*	8±4*
Maximal change in LVP over time (dP/dt)	1376±600	1367±625	1190±700	826±547
Pulmonary artery pressure (mmHg)	25±9	23±6	25±7	24±7
Central venous pressure (mmHg)	10±6	10±6	11±6	11±6
Cardiac output (L/min)	7.6±0.8	7.5±1.2	7.0±1.2	7.1±1.4
Fractional shortening (%)	36.5±1	36.4±0.7	36.3±0.8	36.4±0.7
LVISd/LVIDd (mm)	37.4/56.5	34.1/50.1	31.3/46.4	27.2*/41.5*
RVISd/RVIDd (mm)	19.1/27.1	18.9/27.3	19/26.9	19.2/27.0

\*p<0.05 vs baseline. Values are mean ± SD. bpm: Beats per minute; LVIDd: Left ventricular internal diastolic diameter; LVISd: Left ventricular internal systolic diameter.

**Echocardiographic assessment.** Serial two-dimensional transepical studies were performed at each pump speed. Echocardiographic assessment was accomplished using a Hewlett Packard Sonos 2000 ultrasound system equipped with a 2.5-MHz phased-array transducer, according to the guidelines of the American Society of Echocardiography.<sup>[6]</sup> The echocardiogram was used to measure fractional shortening, LV internal systolic and diastolic dimensions (LVISd and LVIDd), LV, RV and septal wall motion, and aortic valve opening.

**Myocardial oxygen consumption assessment.** An 18-gauge angiocatheter was inserted into the coronary sinus via the azygos vein to take coronary sinus blood samples. One blood sample was taken at baseline and at each pump speed to assess myocardial oxygen consumption (MVO<sub>2</sub>). MVO<sub>2</sub> was approximated as the difference between aortic ( $\bar{a}$ ) and coronary sinus ( $\bar{v}$ ) blood oxygen content, multiplied by the left anterior descending (LAD) coronary artery blood flow rate (CBF) (i.e., MVO<sub>2</sub> = CBF · [ $\bar{a}$  -  $\bar{v}$ ]). A Novastat Profile M blood gas analyzer (Nova Biomedical Co., Waltham, MA) was used for blood gas analysis.

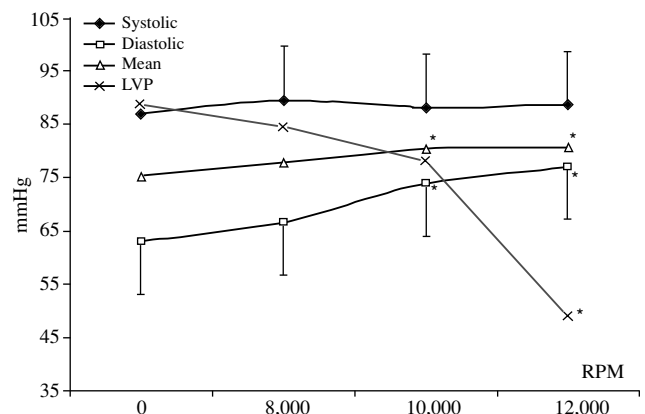
**Statistical analysis.** All statistical tests were performed using SAS on a personal computer. Data were analyzed using ANOVA followed by Student-Newman-Keuls where appropriate. A p value of less than 0.05 was considered significant.

## RESULTS

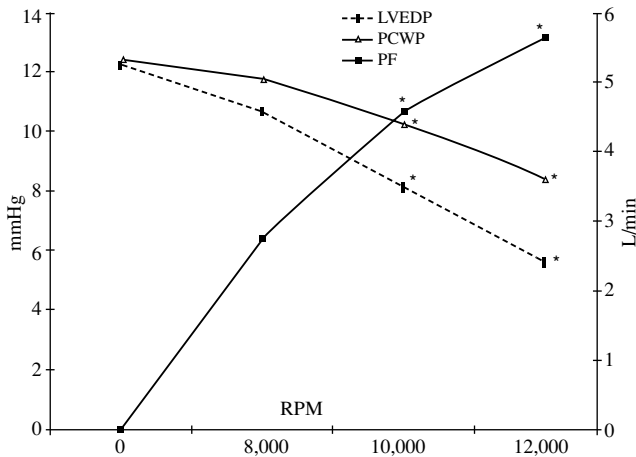
All the calves were successfully implanted with the Jarvik 2000 axial flow pump and experiments were suc-

cessfully completed without surgical or device-related complications. At the conclusion of the experiment, animals were euthanized with an intravenous bolus of potassium chloride given under general anesthesia.

**Hemodynamic data.** Table 1 shows the left and right heart catheterization data. There was no significant change on mean AoPs at increasing pump speeds. However, there was a gradual and statistically significant increase in AoPm and AoPd as the pump speed increased above 10,000 rpm (10,000 and 12,000 rpm vs baseline, p<0.05) (Fig. 1). The increases in mean AoPm and AoPd resulted in narrowed aortic pulse pressure which dropped from 24±7 mmHg at baseline to 12±7 mmHg at 12,000 rpm (10,000 rpm and 12,000 rpm vs



**Fig. 1.** Aortic and left ventricular blood pressures at increasing pump speeds. \*p<0.05 vs baseline; LVP: Left ventricular systolic pressure; RPM: Rate Per minute.

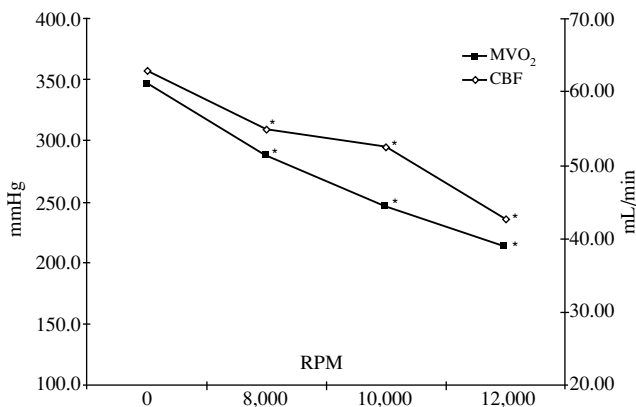


**Fig. 2.** Left ventricular end-diastolic pressure (LVEDP), pulmonary capillary wedge pressure (PCWP), and pump flow (PF) at increasing pump speeds. \* $p < 0.05$  vs baseline. RPM: Rate Per minute.

baseline,  $p < 0.05$ ). Right heart pressures were not affected by increases in pump speeds and remained close to the baseline values.

There was no significant change on the mean LVP between 8,000 and 10,000 rpm; however, a statistically significant decrease was observed at 12,000 rpm ( $p < 0.05$  vs baseline, 8,000 rpm and 10,000 rpm). The gradual decreases in mean LVEDP and PCWP were consistent with the increased pump flow resulting in increased left ventricle unloading ( $p < 0.05$  for LVEDP and PCWP at 10,000 and 12,000 rpm vs baseline) (Fig. 2). The decreases in LVEDP and PCWP were consistent with the increases in pump flow which rose from  $2.75 \pm 0.27$  L/min at 8,000 rpm to  $4.57 \pm 0.55$  L/min at 1,000 rpm and to  $5.63$  L/min at 12,000 rpm ( $p < 0.05$  for all speeds vs 8,000 rpm) (Fig. 2).

There was a significant decrease in the mean CBF at all increasing speeds vs baseline ( $p < 0.05$ ) (Fig. 3).



**Fig. 3.** Coronary blood flow (CBF) and myocardial oxygen consumption (MVO<sub>2</sub>) at increasing pump speeds. \* $p < 0.05$  vs baseline. RPM: Rate Per minute.

Consistent with the fall in CBF, the mean MVO<sub>2</sub> significantly dropped from 346 mL/min/kg at the baseline to 213 mL/min/kg at 12,000 rpm ( $p < 0.05$  at all speeds vs baseline) (Fig. 3). However, increasing pump speeds did not affect the baseline ratio of CBF to MVO<sub>2</sub> which remained between 0.18 and 0.20 throughout the study.

**Echocardiographic studies.** Echocardiographic measurements are listed in Table 1.

There was a gradual but insignificant reduction in internal systolic and diastolic LV dimensions at 8,000 rpm and 10,000 rpm. However, the mean LVISd decreased from  $35.7 \pm 0.5$  mm at the baseline to  $22.7 \pm 2.4$  mm at 12,000 rpm ( $p < 0.05$ ) and the mean LVIDd decreased from  $55.7 \pm 2.6$  mm to  $29.4 \pm 4.4$  mm ( $p < 0.05$ ). Aortic valve opening was impaired in three calves at 12,000 rpm. Right ventricular wall motion and diameters were not adversely affected by increasing pump speed.

## DISCUSSION

In this study, statistically significant increases in AoPd and AoPm pressures were observed at speeds exceeding 10,000 rpm without a significant change in aortic systolic pressure. This effect caused narrowing of the pulse pressure (from 22 mmHg at the baseline to 12 mmHg at 12,000 rpm), which is a result of extensive left ventricle unloading, and reduced native cardiac pulsatility at increasing speeds, as reported in previous clinical and experimental studies. The other cause of narrowed pulse pressure was the reversal of blood flow direction towards the aortic valve and impairment in the aortic valve opening, which is a well-known feature at higher pump speeds when the pump outflow graft is anastomosed to the descending aorta.<sup>[3]</sup> Spontaneous echocardiographic contrast has been demonstrated in the aortic root at higher device speeds with the aortic valve closed,<sup>[7]</sup> and it is possible that, in our study, the blood flow stagnated and/or became turbulated into the aortic root and/or ascending aorta. Although the clinical significance of this finding is not clear, altered flow dynamics and reduced pulsatility in the aortic root may affect coronary artery resistance, flow or thromboembolization, for which further studies are warranted.

The gradual decrease in dp/dt max that we observed at increasing levels of pump support may be attributed to delayed LV relaxation secondary to extensive LV unloading.<sup>[8]</sup> In fact, the gradual decrease in LVP may lead to a decrease in myocardial work.<sup>[9]</sup>

Based on our echocardiographic measurements, fractional shortening (FS) remained unchanged at increasing pump speeds; however, LVIDd and LVIDs decreased, most likely as a result of extensive unloading of the left ventricle.<sup>[8,10]</sup> We suggest that the combi-

nation of decreased left ventricular end-systolic pressure, reduced wall stress, increased aortic diastolic pressure, and increased retrograde flow may result in decreased systolic ejection time and impairment in the aortic valve opening in some cases.

The effect of LVAD support on the right ventricle is still controversial. Some investigators believe that increasing pump support may cause increased venous return and ventricular septal shifting, resulting in impaired RV function.<sup>[11-13]</sup> Others believe that LVAD support does not affect the function of a nonischemic right ventricle.<sup>[14,15]</sup> In our study, RV echocardiographic measurements were not affected by increasing LVAD supports; however, our results were obtained in a healthy animal model and, thus, may not be comparable to observations in patients with end-stage heart failure.

In the present study, the cardiac output was measured by a Swan-Ganz catheter and it may not reflect exactly the changes of the left heart output since the left ventricle has two outputs, namely the aortic valve and the axial flow pump outflow graft. The contribution of the pump flow to the left heart output was almost 40% when the pump was operating at 8,000 rpm; however, it increased to 77% at 12,000 rpm and resulted in significant left ventricular unloading. This phenomenon caused decreased left ventricular oxygen consumption at increasing pump speeds. Therefore, the gradual decreases in CBF and  $MVO_2$  at increasing pump speeds may be attributed to extensive unloading of the left ventricle and to reduced energy demand secondary to decreased LV wall tension, as previously stated in several studies.<sup>[16-19]</sup> However, despite the decreases in CBF and  $MVO_2$  at increasing speeds, the CBF/ $MVO_2$  ratio remained almost constant throughout the speed changes, indicating that the decreases in CBF and  $MVO_2$  were proportional to the decreased workload of the unloaded left ventricle and did not impair LV performance. This was in concordance with intraoperative hemodynamic and echocardiographic measurements. Our results are consistent with experimental findings of Merhige et al.<sup>[20]</sup> and Smalling et al.,<sup>[21]</sup> who showed that coronary perfusion of the non-ischemic myocardium decreased following ventricular unloading. However, our experiments were performed in the acute setting when autoregulatory mechanisms were at work; consequently, the present findings do not necessarily warrant any conclusions about the long-term effects of continuous flow on the coronary blood flow. Moreover, it's not possible to exclude the effect of anesthesia on aortic and myocardial blood flow properties.

In conclusion, we suggest that despite the decreases in CBF at increasing pump speeds as a result of reduced

cardiac work, the CBF/ $MVO_2$  ratio remains constant and does not impair normal LV function.

## REFERENCES

1. Cooley DA. Initial clinical experience with the Jarvik 2000 implantable axial-flow left ventricular assist system. *Circulation* 2002;105:2808-9.
2. Muller J, Wallukat G, Weng YG, Dandel M, Spiegelsberger S, Semrau S, et al. Weaning from mechanical cardiac support in patients with idiopathic dilated cardiomyopathy. *Circulation* 1997;96:542-9.
3. Frazier OH, Myers TJ, Gregoric ID, Khan T, Delgado R, Croitoru M, et al. Initial clinical experience with the Jarvik 2000 implantable axial-flow left ventricular assist system. *Circulation* 2002;105:2855-60.
4. Macris MP, Parnis SM, Frazier OH, Fuqua JM Jr, Jarvik RK. Development of an implantable ventricular assist system. *Ann Thorac Surg* 1997;63:367-70.
5. Tuzun E, Eya K, Chee HK, Conger JL, Bruno NK, Frazier OH, et al. Myocardial hemodynamics, physiology, and perfusion with an axial flow left ventricular assist device in the calf. *ASAIO J* 2004;50:47-53.
6. Henry WL, DeMaria A, Gramiak R, King DL, Kisslo JA, Popp RL, et al. Report of the American Society of Echocardiography Committee on Nomenclature and Standards in Two-dimensional Echocardiography. *Circulation* 1980;62:212-7.
7. Nicolson DG, Porto I, Westaby S, Boardman P, Banning AP. Spontaneous echocardiographic contrast in the ascending aorta mimicking the appearance of aortic dissection in a patient with a left ventricular assist device. *Echocardiography* 2004; 21:193-5.
8. Saito A, Shiono M, Orime Y, Yagi S, Nakata KI, Eda K, et al. Effects of left ventricular assist device on cardiac function: experimental study of relationship between pump flow and left ventricular diastolic function. *Artif Organs* 2001;25:728-32.
9. Shiiya N, Zelinsky R, Deleuze PH, Loisanse DY. Effects of Hemopump support on left ventricular unloading and coronary blood flow. *ASAIO Trans* 1991;37:M361-2.
10. Westaby S, Jin XY, Katsumata T, Taggart DP, Coats AJ, Frazier OH. Mechanical support in dilated cardiomyopathy: signs of early left ventricular recovery. *Ann Thorac Surg* 1997; 64:1303-8.
11. Holman WL, Bourge RC, Fan P, Kirklin JK, Pacifico AD, Nanda NC. Influence of left ventricular assist on valvular regurgitation. *Circulation* 1993;88(5 Pt 2):II309-18.
12. Moon MR, Castro LJ, DeAnda A, Tomizawa Y, Daughters GT 2nd, et al. Right ventricular dynamics during left ventricular assistance in closed-chest dogs. *Ann Thorac Surg* 1993;56:54-66; discussion 66-7.
13. Farrar DJ, Compton PG, Hershon JJ, Fonger JD, Hill JD. Right heart interaction with the mechanically assisted left heart. *World J Surg* 1985;9:89-102.
14. Shuman TA, Palazzo RS, Jaquiss RB, Harper BD, Barzilai B, Cox JL, et al. A model of right ventricular failure after global myocardial ischemia and mechanical left ventricular support. *ASAIO Trans* 1991;37:M212-3.
15. Chow E, Brown CD, Farrar DJ. Effects of left ventricular pressure unloading during LVAD support on right ventricular contractility. *ASAIO J* 1992;38:M473-6.

16. Frazier OH, Myers TJ. Left ventricular assist system as a bridge to myocardial recovery. *Ann Thorac Surg* 1999;68: 734-41.
17. Maybaum S, Epstein S, Beniaminovitz A, Oz M, Bergman S, Mancini D. Resting myocardial blood flow and metabolism predicts improved native cardiac output and the ability to exercise with weaning in patients with the TCI HeartMate left ventricular assist device. *J Am Coll Cardiol* 1999;33(2 Suppl 1):219A.
18. Belloni FL. The local control of coronary blood flow. *Cardiovasc Res* 1979;13:63-85.
19. Feigl EO, Neat GW, Huang AH. Interrelations between coronary artery pressure, myocardial metabolism and coronary blood flow. *J Mol Cell Cardiol* 1990;22:375-90.
20. Merhige ME, Smalling RW, Cassidy D, Barrett R, Wise G, Short J, et al. Effect of the hemopump left ventricular assist device on regional myocardial perfusion and function. Reduction of ischemia during coronary occlusion. *Circulation* 1989;80(5 Pt 2):III158-66.
21. Smalling RW, Cassidy DB, Barrett R, Lachterman B, Felli P, Amirian J. Improved regional myocardial blood flow, left ventricular unloading, and infarct salvage using an axial-flow, transvalvular left ventricular assist device. A comparison with intra-aortic balloon counterpulsation and reperfusion alone in a canine infarction model. *Circulation* 1992; 85:1152-9.