Published in final edited form as:

J Heart Lung Transplant. 2010 January ; 29(1): 32–36. doi:10.1016/j.healun.2009.09.004.

Introduction of Fixed-Flow Mode in the DexAide Right Ventricular Assist Device

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Abstract

Background—While some continuous-flow left ventricular assist device algorithms have been created to respond to varying patient physiology, very little research has been conducted on control of right ventricular support in univentricular and biventricular applications. The purpose of this study was to develop and evaluate a simple and reliable fixed-flow algorithm for the DexAide right ventricular assist device (RVAD). This algorithm automatically adjusts speed to maintain a target flow while preventing ventricular suction when a requested target flow exceeds available tricuspid flow.

Methods—Fixed-flow control mode was evaluated in 17 DexAide RVAD chronic bovine studies whose duration ranged from 14 - 90 days (33 ± 24 days). Targeted fixed-flow levels ranged from 4.0 to 6.5 L/min. Data were monitored on an hourly basis. Pump flow data were also recorded on a weekly basis to document the speed increment required to increase pump flow from 5 to 8 L/min at 0.5 L/min increments.

Results—The fixed-flow control mode was evaluated for a total duration of 5,283 hours without complications related to pump flow or left/right circulation imbalance. The pump speed varied between 2,000 – 3,220 rpm to maintain the flow constant at each target level. The average absolute mismatch between the target flow and measured flow was 0.6 ± 0.5 L/min.

Conclusions—Fixed-flow control mode with a predetermined maximum automatic pump speed can be safely and effectively used in the DexAide RVAD. It provided target flows by adjusting the pump speed while monitoring pump flow response to automatic speed increment requests.

In recent years, seeking an alternative to the traditional pulsatile mechanical circulatory support systems, researchers have focused on continuous-flow systems because they are generally smaller and more reliable and require less anticoagulation compared to the pulsatile-flow devices. However, pulsatile devices are generally preload sensitive and thus efficient at adapting to the patient's physiological condition with a Frank-Starling like response to venous return. Continuous-flow pumps, in contrast, are generally much more afterload sensitive devices, making it more difficult to respond to varying patient preloads.¹ In patients requiring biventricular assist device (BVAD) support, an additional complication is the limited ability

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Presented at the 16th annual congress of the International Society for Rotary Blood Pumps, Houston, Texas, October 2-4, 2008.

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of continuous-flow pumps to respond to left/right flow imbalances caused by “mismatching” of left and right pump support. While some continuous-flow left ventricular assist device (LVAD) algorithms have been created to respond to varying patient physiology in univentricular applications, very little research has been conducted on control of right ventricular support in either univentricular support or for the more complex left/right flow issues presented by biventricular applications.

The DexAide right ventricular assist device (RVAD) design has been adapted from the CorAide™ LVD-4000 Assist System (Arrow International, Reading, PA) and is currently undergoing development at the Cleveland Clinic.²⁻⁴ DexAide RVAD control system is designed to support patients in fixed-speed, fixed-flow mode or in biventricular assist device (BVAD) mode. The purpose of this *in vivo* study was to develop and evaluate a reliable fixed-flow algorithm for the DexAide continuous-flow RVAD that could automatically adjust speed to compensate for varying right ventricular afterload and preload while preventing ventricular suction when a requested target flow exceeds the flow through the tricuspid valve.

Material and Methods

Animal Model

This study was approved by the Cleveland Clinic's Institutional Animal Care and Use Committee. DexAide RVADs were implanted chronically in 17 Holstein calves with normal cardiac function (range 88.8-160 kg, mean 107 ± 19 kg). All animals received humane care in compliance with the ‘Principles of Laboratory Animal Care’ formulated by the National Society for Medical Research and the ‘Guide for the Care and Use of Laboratory Animals’ prepared by the Institute of Laboratory Animal Resources and published by the National Institutes of Health (NIH Publication No. 86-23, revised 1996).

Surgical Procedures

A fourth intercostal thoracotomy was performed. Fluid-filled pressure monitoring lines were inserted to monitor arterial blood pressure, central venous pressure, left atrial pressure, and pulmonary arterial pressure. A 28-mm Transonic ultrasonic perivascular flow probe (Transonic Systems Inc., Ithaca, NY) was placed on the pulmonary artery or ascending aorta to measure total cardiac output. Cardiopulmonary bypass was initiated. The outflow conduit was sutured to the pulmonary artery in an end-to-side fashion. The inflow cannula was inserted into the right ventricle. A 16-mm ultrasonic (Transonic Systems Inc., Ithaca, NY) probe was placed on the pump outflow graft to monitor pump flow.

Fixed-Flow Algorithm

The fixed-flow algorithm adjusts the speed of the DexAide RVAD pump to meet a requested target flow. Figure 1 illustrates the programming logic for maintaining pump flow constant and includes logic to prevent ventricular suction whenever a requested target flow exceeds the flow through the tricuspid valve. This control algorithm is implemented when the clinician programs a target RVAD pump flow to match the hemodynamic needs of each patient. The pump controller maintains the pump speed constant over a fixed 10-s duration control interval, then calculates the mean pump flow for that control cycle. The difference between the programmed target flow and the calculated pump flow would then determine if the pump speed should be increased, decreased or left unchanged for the next control cycle interval. If the absolute difference in values for the target and calculated flow values is $<5\%$, the pump speed is left unchanged. If the difference is $>5\%$, a fixed step increase or decrease in speed is implemented and the new pump speed is maintained over the next control cycle. The speed increment/decrement is set at ± 75 rpm. The pump speed is then automatically and iteratively changed over several 10-s control cycles until the calculated mean pump flow matches the

desired target flow for the current physiologic conditions. The 10 s average is used to filter out the transient effects of respiration and changes in venous return due to increases in abdominal pressure from straining. The interval is limited to 10 s to adequately respond to transient changes in physiology which may be sustained for several minutes to hours such as acute onset changes in cardiac function due to factors such as arrhythmia or due to transient changes in afterload.

This control logic, however, is overridden by logic used to sense a pre-suction state in the right ventricle caused by excessive ventricular unloading. In addition to calculating mean pump flow at the end of each 10-s control cycle, the change in calculated pump flow from the previous cycle is calculated (flow change: d_{flow}). It is assumed in the algorithm that if the right ventricle has adequate volume and the RVAD has just increased pump speed in the previous cycle, there will be a minimum expected increase in calculated pump flow or a minimum expected d_{flow} . If the d_{flow} after an increase in speed (speed change: d_{speed}) does not exceed this limit, the ventricle is assumed to be unloaded with little more pump output achievable from further speed increases. The use of the $d_{\text{flow}}/d_{\text{speed}}$ ratio to predict ventricular volume status has been described previously by Antaki *et al.*⁵ In our current setting, the minimum expected flow change after an increment in pump speed of 75 rpm has been evaluated at 0.05 to 0.15 L/min. If this pre-suction condition is detected, the fixed-flow logic is ignored and pump speed is decreased even if calculated pump flow is significantly lower than the target flow. The speed decrement in this condition is set to be a value greater than the speed step change setting described above. This decrement in pump speed is set at 100 rpm or at 25 rpm higher than the speed increment setting. Using this decrement setting will allow the system to slowly ramp down to a lower speed if the target flow is set too high or if there is a transient decrease in right ventricular volume.

Instrumentation and Hemodynamic Data Acquisition

In the first few days after pump implantation, the RVAD was maintained at fixed-speed mode. After postoperative hemodynamic stabilization, the fixed-speed mode was then switched to fixed-flow mode at different flow rates for varying durations during the course of each study. The automatic pump speed adjustments were maintained in the majority of the studies between 2,100 and 2,800 rpm.

To document the rate of pump flow increment for a given speed increment, pump flow and speed were also recorded weekly using a PowerLab data acquisition system (ADInstruments, Inc., Mountain View, CA) by adjusting pump speed to achieve increasing target pump flow from 5 to 8 L/min in 0.5 L/min increments. During data acquisition, calves were maintained in a standing position in the chronic care unit. Data are described as mean $\pm$ standard deviation. The Bivariate correlation coefficient (r) was used to determine the correlation between the target flow and the resulting measured pump flow and speed.

Results

The study duration for the 17 implants ranged from 14 - 90 days (33 ± 24 days). Fixed-flow mode was tested for a total duration of 5,283 hours. The mean pump flow and speed during the study was 5.6 ± 0.9 L/min and $2,516 \pm 148$ rpm respectively. Average motor power consumption was 2.7 ± 1.0 Watts. Table 1 shows average data obtained during these chronic experiments for each level of target flow tested. The pump speed varied between 2,000 – 3,220 rpm to maintain the flow constant at each target level. Figure 2 shows representative pump speed data from a 30-day study to demonstrate how the pump speed changes to maintain each target pump flow. In this experiment, the pump was run at fixed speed mode for the first 5 days then switched to fixed-flow mode with 3 different target pump flow levels.

The absolute mismatch in measured flow and targeted flow in these studies averaged 0.6 ± 0.5 L/min. Maximum and minimum recorded differences between measured flow and targeted flow were 2.9 L/min and -3.1 L/min, respectively.

The mean total cardiac output during fixed-flow mode operation was 12.0 ± 2.8 L/min. The mean AP and PAP were 95 ± 10 mm Hg and 25 ± 7 mm Hg, respectively. The mean CVP and LAP were 7 ± 5 mm Hg and 9 ± 5 mm Hg, respectively. No relevant left/right circulation imbalance or ventricular suction was observed in any of these studies.

The results of the weekly recorded data studying the relationship between targeted pump flows in 0.5 L/min increments (5.0 to 8.0 L/min) vs. measured pump flow and required pump speed were positively correlated with targeted pump flow (correlation coefficient = 0.996 and 0.998 respectively). Figure 3 shows the positive correlation between various targeted and resulting measured pump flows with a linear relationship defined by a 0.99 L/min increment in measured flow for every 1.0 L/min increment in targeted flow. Figure 4 shows the positive correlation between targeted pump flow and resulting controller adjusted pump speed with a linear relationship defined by a 341 rpm increment in pump speed required for every 1.0 L/min increment in targeted pump flow.

Discussion

This study has demonstrated the feasibility of using a fixed-flow operating mode in the DexAide RVAD. This flow mode with a predetermined maximum automatic pump speed was tested for 5,283 hours without any left/right circulation imbalances, pulmonary congestion, or ventricular suction.

The major drawback of commonly used continuous-flow pumps is their limited intrinsic adaptation to changes in venous return and sensitivity to variations in afterload, which makes adjustment of pump speed necessary. It has been reported that even when these pumps are maintained at a constant speed, changes in the residual pumping activity of the natural heart can result in some adaptation of pump flow to physiologic demand.⁶ However, this response remains below the natural response defined by the Frank-Starling mechanism.⁷ These aforementioned intrinsic characteristics of continuous-flow pumps necessitate the development of a reliable control algorithm that can immediately adapt pump speed and flow to changing physiological conditions. Research has recently focused on control systems for use when continuous-flow pumps are implanted as LVADs.⁸⁻¹¹ Several automatic modes have been developed and tested to support the left side circulation.⁹⁻¹² Most continuous-flow LVADs currently in clinical trials primarily use a fixed-speed control mode. The CorAide LVAD automatic control scheme, which was also developed at Cleveland Clinic, used automatic control of the pump output for the majority of the total implant duration in its European clinical trial and was the preferred operating mode for outpatients.¹³ The details about the aforementioned clinical trial will be published separately. This algorithm relies on sensed heart rate, pressure differential across the pump and pump flow pulsatility to be implemented.

The significantly lower pressure and pump flow pulsatility characteristics of right-heart support requires development of a different control system for right-side circulation. A literature search in the field of mechanical circulating support systems failed to reveal any significant work being done regarding RVAD control modes. Yoshikawa *et al.*¹⁴ proposed using heart rate and oxygen uptake as feedback parameters for controlling the flow rate during exercise with rotary blood pump. Those investigators made their conclusion based on the fact no changes in the RVAD pump flow were observed during exercise. As the implantation of an RVAD is usually performed in patients with existing LVAD support, a control system developed for RVAD

must work in BVAD applications as well. This fact further complicates the development of a reliable control system for RVAD.

The simpler fixed-flow algorithm, described here, is particularly advantageous for RVAD application. Based on our previous animal nonpulsatile perfusion studies using continuous-flow BVAD support of a fibrillated heart, it was shown that pulmonary circulation was maintained at 2 to 3 L/min with the RVAD pump off and the heart fibrillated.¹⁵ This residual flow may be explained by the presence of the so called “atrial kick”. This theory is further supported by previous clinical reports of patients on LVAD support surviving ventricular fibrillation due to pulmonary circulation pass through to the left ventricle. Therefore, we believe that operating a continuous-flow RVAD in a fixed flow condition that captures at least 75% of the resting pulmonary circulation may provide sufficient assisted flow at any pulmonary vascular resistance and any level of right ventricular dysfunction. This does not work as well when applied to LVAD support that requires both cardiac output and much higher pump differential pressure in the range of 60 to 90 mm Hg due to higher systemic vascular resistance. Moreover, the pulsatility in the motor current, motor power and/or derived pump flow pulsatility, which is typically used in many continuous-flow LVAD automatic control schemes, is less reliable as a control feedback in RVAD applications because of the much lower afterload in the pulmonary circulation. The fixed-flow mode is implemented by adjusting pump speed to achieve a predetermined targeted pump flow based on the hemodynamic needs of the patient. The study investigated the effectiveness of defined speed adjustment steps as a result of differences in calculated pump flow and target flow over a 10-s fixed-speed control cycle. Furthermore, the average change in pump flow response to a 75 rpm speed increment over a 10-s control cycle is used in this control mode to detect pre-suction states and prevent excessive unloading of the right ventricle.

Fixed flow mode has several advantages over fixed speed mode; it adjusts pump speed to maintain flow in the face of changes in afterload. However, in fixed speed mode, pump output changes in the face of changing afterload. Also, fixed flow mode prevents suction events in the absence of adequate volume in the ventricles by decreasing pump speed if a minimum change in calculated pump flow from the previous cycle (flow change: d_{flow}) is not achieved with any step increase in pump speed required to maintain a fixed flow level. Another advantage of the fixed flow mode is the possibility of adjusting the pump flow to the patient's functional status, which is of particular importance in the setting of BVAD, in which the RVAD responds by changing the pump speed based of LVAD flow pulsatility.

An important application of this DexAide RVAD control mode is in a biventricular control algorithm for simultaneous control of the DexAide RVAD and CorAide LVAD. DexAide RVAD control system is designed to support patients in fixed-speed, fixed-flow mode or in BVAD mode. This BVAD control mode is particularly challenging as one must maintain proper right-left flow and atrial pressure balance. We have previously shown, in acute bovine BVAD experiments looking at the effects of varying levels of left and right ventricular support, the importance of adjusting the left pump speed and flow to be higher than that of the right pump and limiting the RVAD maximum operating speed to 2,400 rpm to avoid possible imbalance between right and left circulation.¹⁵ In our DexAide/CorAide BVAD control scheme, the CorAide pump is set to automatic mode, in which the pump speed is adjusted to obtain a target flow, while using the flow pulsatility to avoid possible left ventricular suction. The target flow varies based on sensed heart rate and afterload. Under BVAD control mode, the RVAD runs in fixed-flow control mode until the CorAide controller communicates a low LVAD flow pulsatility state to the RVAD controller, indicating excessive left ventricular unloading by the LVAD. In this case, the RVAD responds by increasing its pump speed and output until the LVAD flow pulsatility increases or the RVAD controller senses excessive right ventricular unloading. As proper testing of this BVAD control mode must be carried out in the presence

of chronic heart failure, we are currently developing a bovine chronic heart failure model and plan to test this BVAD control scheme after experimentally creating heart failure.

Limitations of this study include that the study was performed in animals with normal cardiac function and relatively higher cardiac output than that of the targeted patients. Furthermore, the study describes the use of only RVAD and is not evaluating the feasibility of using this flow mode in the BVAD setting, which is of particular importance as the majority of targeted patients would have the RVAD placed in the presence of LVAD. Finally, the fixed flow mode was not evaluated in animals during exercise, for instance using treadmill physiologic or other pump performance studies, which may provide better input regarding the feasibility of this flow mode.

In conclusion, fixed-flow mode with a predetermined maximum automatic mode pump speed can be safely and effectively used in the DexAide RVAD. The DexAide safely and effectively sustained targeted flows by adjusting the pump speed while monitoring of $d_{\text{flow}}/d_{\text{speed}}$ to detect a pre-suction condition. The limited maximum speed in fixed-flow mode is intended to prevent overdriving flow into the pulmonary circulation. Evaluation of this control mode in a chronic heart failure animal model and in continuous-flow biventricular support applications is needed to validate pre-suction detection and the protection of the pulmonary circulation.

Acknowledgments

Disclosures: The work reported here was funded by Bioengineering Research Partnerships grant 5R01HL074896 (to K.F.) from the National Heart, Lung, and Blood Institute/NIH.

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FIG. 1.
Fixed-flow control algorithm. The flow change limit is set at 0.05-0.15 L/min.

FIG. 2.

Representative pump speed data from a 30-day study to demonstrate how the pump speed changes to maintain the target pump flow. FS, fixed speed; FF, fixed-flow; lpm, liters per minute.

FIG. 3.
Correlation between targeted pump flow and resulting average measured pump flow.

FIG. 4.
Correlation between targeted pump flow and resulting average pump speed.

TABLE 1

Average data obtained during chronic in vivo experiments with the DexAide RVAD in Fixed-Flow control mode.

Fixed-flow test duration (Hours)	Target fixed-flow (L/min)	Measured flow (L/min)	Speed (Mean $\pm$ SD) (rpm)
42	4.0	4.0 $\pm$ 0.1	2,266 $\pm$ 76
113	4.5	4.2 $\pm$ 0.6	2,746 $\pm$ 120
662	5.0	4.9 $\pm$ 0.3	2,510 $\pm$ 199
1,673	5.5	5.5 $\pm$ 0.1	2,457 $\pm$ 132
2,035	6.0	5.9 $\pm$ 0.3	2,525 $\pm$ 125
758	6.5	6.5 $\pm$ 0.1	2,604 $\pm$ 113