

# Design of a DSP Controller for an Innovative Ventricular Assist System

MINGHUA FU,\* LONGYA XU,\* ALEXANDER MEDVEDEV,† WILLIAM A. SMITH,† AND LEONARD A. R. GOLDING†

**The design and development of the digital signal processor controller for an innovative ventricular assist system is presented. A DSP56005 is used as the central processor, with other peripheral components. System hardware and software were developed through the advanced development system, and stand alone operation of the system was also accomplished. Two different control modes—current control mode and speed control mode—were developed and investigated. Performance of efficiency and dynamic response were examined through experimental testing. *ASAIO Journal* 1997; 43:M615–M619.**

The design of the motor drive circuit and its controller for an innovative ventricular assist system (IVAS) is intended for permanent implant in humans. High performance, small size, and very high reliability are essential, and low cost is desirable. The motor circuit must control the operation of a permanent magnet (PM) machine which, for size and mechanical simplicity, is commutated by a sensorless technique. The motor driver must adjust its output in accordance with command signals provided by the physiologic controller, and any diagnostic logic built into the IVAS. The motor circuit must also output signals relevant to monitoring pump and motor operation. In principle, the motor circuitry may have one of two fundamental architectural concepts: analog or digital. In a previous study, The Cleveland Clinic/Ohio State University design team had evaluated both, theoretically and experimentally. This study clearly favored a digital approach to motor circuitry for implantable blood pumps. Motorola's DSP56005 is used in the digital control system, which offers major advantages with respect to achieving efficient, robust, and responsive motor operation. Different sensorless control algorithms can also be effectively implemented and evaluated by using a digital signal processor (DSP). Current and speed control schemes are conveniently implemented to maximize motor efficiency and dynamic response. Through a DSP controller, bidirectional communication with the physiologic control system and diagnostic monitoring is very flexible. Significantly, new generations of software can be designed and implemented quickly and efficiently, when experience indicates the most effective, reliable, and fail-safe system.

## Design of the DSP Control System

The block diagram of the DSP56005 based digital motor controller system is shown in **Figure 1**. The system is composed

From the \*Department of Electrical Engineering, The Ohio State University, Columbus, Ohio, and the †Department of Biomedical Engineering, Cleveland Clinic Foundation, Cleveland, Ohio.

Reprint requests: Longya Xu, PhD, Department of Electrical Engineering, The Ohio State University, 2015 Neil Avenue, Columbus, OH 43210.

of the DSP56005 application system, the development system, and the driver circuit. Digital control is realized and the control algorithm is software programmable.

## DSP Application System

The DSP56005 is a general purpose DSP designed for control and embedded applications. It is the expanded version of the DSP56000 family, with fast instruction cycles, powerful arithmetic calculations, flexible interface capabilities, and a compact package. With a 50 MHz clock frequency, one instruction cycle takes only 40 nsec. It has a single-cycle 24 by 24 bit parallel multiply-accumulator, and an advanced parallel instruction set.<sup>3,4</sup>

As shown in **Figure 1**, the IVAS DSP application system consists of:

- The DSP56005.
- Address Decoder. This element is required for proper operation of the peripherals. AMD's Erasable Programmable Logic Device (EPLD) Mach210 is used. The use of EPLD greatly reduces hardware complexity, enhances reliability, and makes the system more compact, which is important for an IVAS.
- A/D Converter. All the analog signals including feedback currents, control voltages, physiologic inputs, etc. need to be converted to digital signals for proper processing. Analog Device's AD7891 is used. It has eight channels and a throughput time of 2.2  $\mu$ sec. Choosing the A/D converter with multiple channels enhances the system compactness and also makes the system very flexible and easily expandable. The fast process of the A/D conversion also gives the system high dynamic response.
- D/A Converter. It will output the diagnostic signals and command voltages. Analog Device's AD7847 dual converter is used.
- Bootstrap EPROM. The 27256 is used. During the bootstrap process, the program is downloaded and rearranged from the 8-bit EPROM to the 24-bit program RAM of the DSP.
- Others. This includes displays, control keys, etc.

## Driver

The drive circuit is mainly composed of power MOSFET and driver chips. The power MOSFET has the advantage of being capable of high switching frequency and, thus, can improve motor performance. In this implementation, a switching frequency of 25 kHz is used. The block diagram of the motor drive circuit is shown in **Figure 2**.

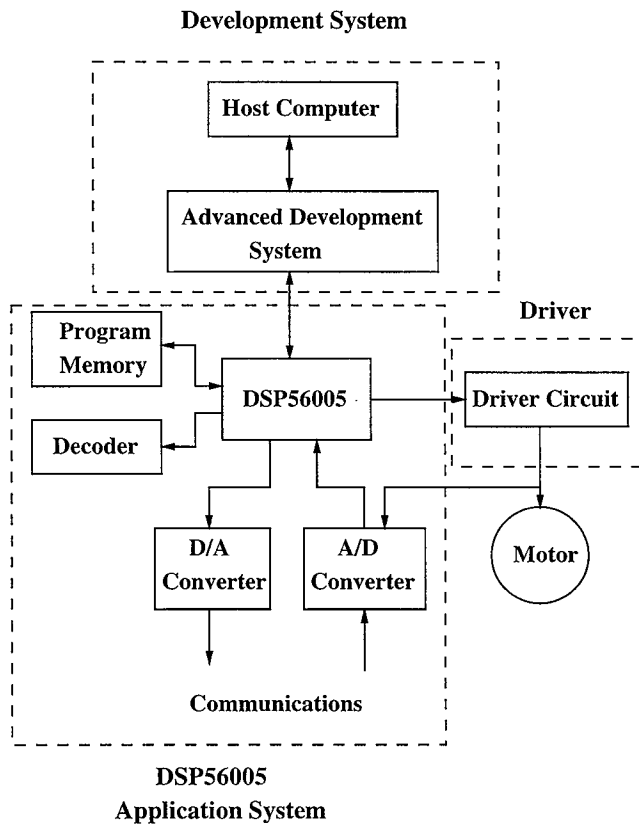


Figure 1. Block diagram of the DSP56005 system.

Two Types of DSP Systems

Two types of DSP systems were developed: a development type and a stand alone type.

Development System

In a development system, the DSP is interfaced with the host PC through the advanced development system (ADS), as shown

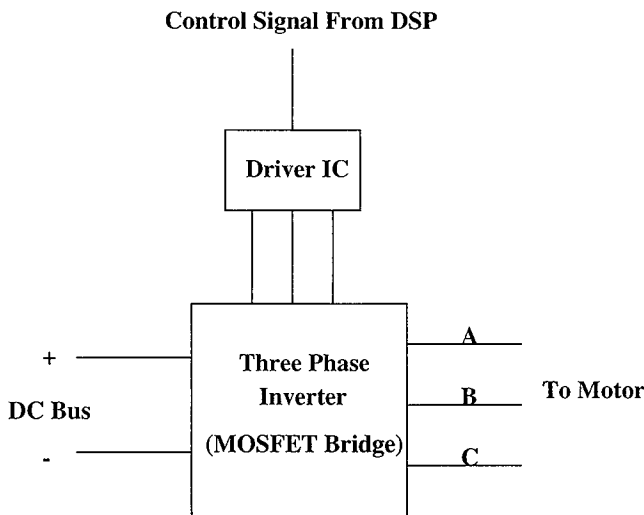


Figure 2. Block diagram of the motor driver.

in Figure 1. Software is developed in the host PC and downloaded into the DSP system through the ADS, and the host PC controls the execution process of the DSP system. It is very convenient for the system designer to debug both hardware and software, because the software can be easily modified, compiled, and downloaded from the PC, and the execution process can be conveniently controlled.

Stand Alone System

In a stand alone system, the execution process of the system software is no longer controlled by the host PC. The software has been programmed into the external program memory (EPROM) (Figure 2). The DSP56005 has an advanced bootstrap feature. After system reset, the DSP can automatically execute a bootstrap program that can download the program from the external memory into the internal memory for execution. In this process, although the DSP56005 is a 24-bit processor, whereas most EPROMs are only 8-bit, the bootstrap program can rearrange the 8-bit code into the 24-bit executable code. Such a design can reduce the physical size of the system, because only one 8-bit EPROM is needed for the 24-bit processor.

The stand alone controller is used in the finalized system. The process continues execution until a system reset. Software can only be changed by reprogramming the EPROM.

Features of the DSP Controller

By using the DSP as the central processor, performance and flexibility are greatly enhanced. Important features include the following.

Advanced digital control algorithms can be implemented by software approach through the DSP. Different control modes can be easily programmed and optimized by means of the powerful arithmetic calculation and data processing capabilities of the DSP, which are very difficult to implement in a low level microprocessor and unimaginable with an analog approach.

Advanced interfacing capabilities of the DSP can achieve sophisticated control and communication for an efficient, reliable, and responsive system. Control and switching mode can be easily adjusted. The system can conveniently communicate with physiologic and diagnostic equipment.

The IVAS motor can operate as a PM synchronous motor (PMSM), which needs a sinusoidal drive current, or as a brushless DC motor (BLDC), which uses a rectangular drive current. By means of the DSP, current and voltage waveforms can be conveniently reshaped through a software approach. It must be noted that two different sensorless techniques are used for PMSM and BLDC operations. When the IVAS motor operates as a PMSM, an indirect position and speed estimation approach is used.<sup>1</sup> For a BLDC motor, the back Electro-Motive-Force (EMF) measurement technique provides information for motor commutation and speed feedback.<sup>2</sup>

Performance of the system can be adjusted to best fit the characteristics of the blood pump under specific load conditions. A digital approach makes it easier for software upgrade and fine tuning of the system.

Control of the System

The IVAS controller has two fundamental operation modes, current control and speed control.

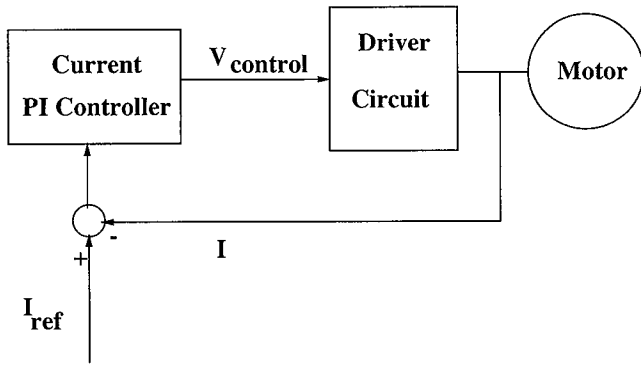


Figure 3. Block diagram of current control of the innovative ventricular assist system motor.

Current Control Mode

The current control mode operation is illustrated in Figure 3. In this case, with a current feedback loop, the motor current can always follow the command current. The motor torque is directly proportional to the current:

$$T_e = K_T I \quad (1)$$

where  $T_e$  is the motor electromagnetic torque,  $I$  is the motor current, and  $K_T$  is the torque constant related to the structure and magnetic field of the motor. Therefore, constant current operation is equivalent to constant torque operation.

The current control of the IVAS motor allows the system to operate with high dynamic response. Because the current directly reflects the torque, this control strategy can assure that the system has a very fast dynamic response. The system can always be controlled to produce the required torque for a given blood flow.

Speed Control Mode

The speed control strategy is illustrated in Figure 4.

The speed control for the IVAS motor is used to secure high speed tracking performance. With the speed feedback control, the IVAS motor will operate at a desired speed in spite of changes in the pump inlet to outlet pressure differences.

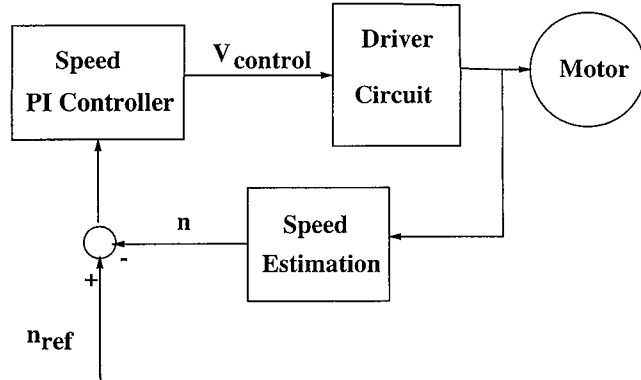


Figure 4. Block diagram of speed control of the innovative ventricular assist system motor.

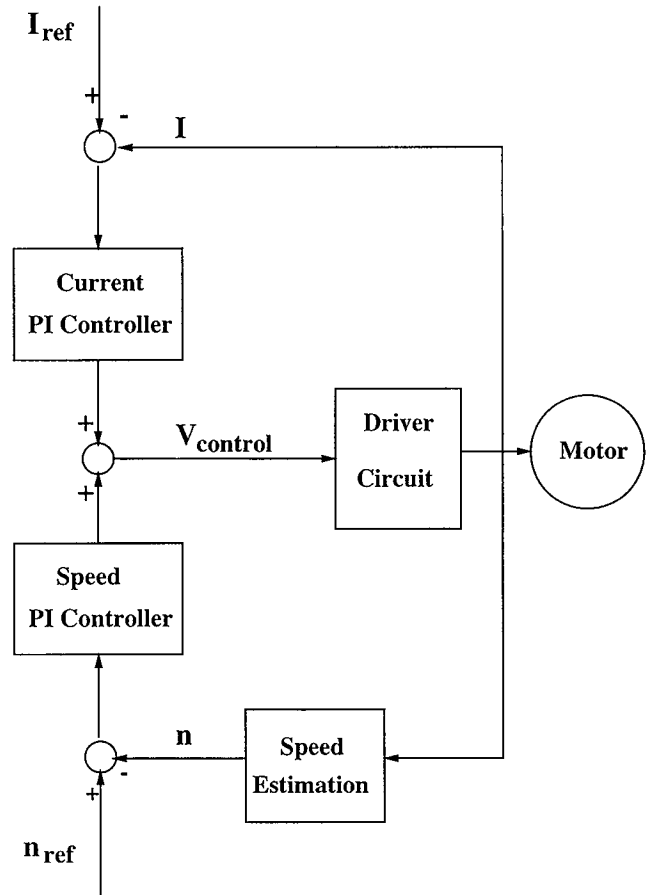


Figure 5. Block diagram of combined control of the innovative ventricular assist system motor.

Combined Current and Speed Control Mode

In reality, no strictly constant current or speed is desirable. The real control strategy of the IVAS motor is a programmable combination of current and speed modes, as shown in Figure 5. By using the speed and current feedback control, high dynamic response can be achieved, with the command speed and command current being functions of some physiologic input. By means of DSP, the combined characteristic can be software programmable and adjustable to give the most appropriate performance for specific patients with various blood pumping characteristics.

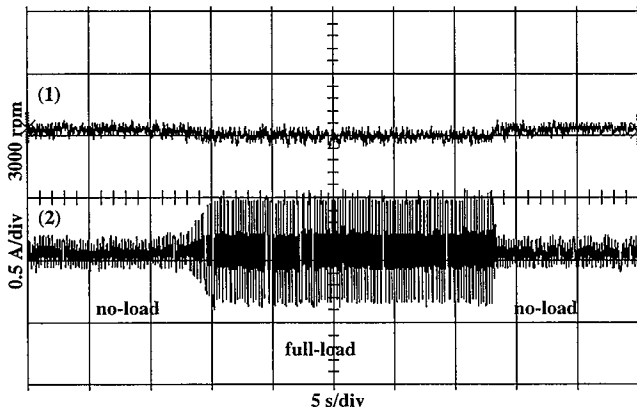
Experimental Results

The prototype controller for the IVAS was completed, and initial experimental results are described as follows.

Figure 6 shows the performance (speed and current) of the IVAS motor in PMSM mode. The system has been tuned to a combined characteristic, with a soft speed to load performance ratio, that is, motor speed changes with torque load.

Figure 7 shows the speed performance of the BLDC during significant change in load. The speed response is strong, but can be changed to soft by changing the parameters of the controller.

The phase current in PMSM corresponding to open-loop/no-load and closed-loop/full-load are shown in Figure 8. It is



**Figure 6.** Speed and phase current of the innovative ventricular assist system motor in permanent magnet synchronous motor mode. *Upper:* Speed. *Lower:* Current.

apparent from the current waveforms that with field orientation closed-loop control, the phase current of the IVAS motor is significantly reduced, hence greatly improving efficiency.

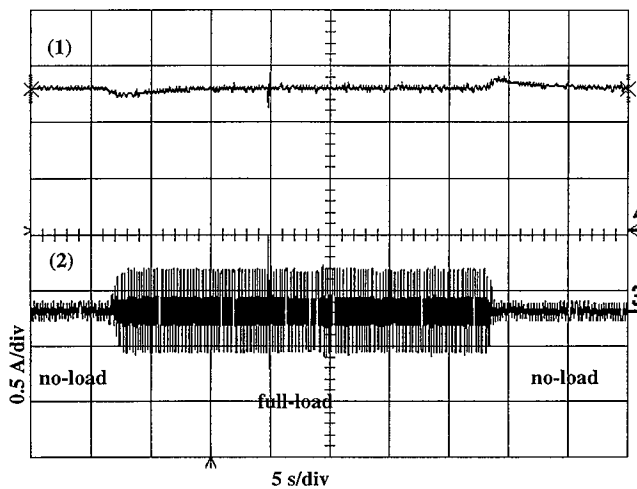
The phase current in BLDC corresponding to no-load and full-load is shown in **Figure 9**. It can be seen that under no-load, or light-load, Pulse Width Modulation (PWM) chopping is significant and, hence, the switching loss is relatively large.

Speed tracking under step command is shown in **Figure 10**.

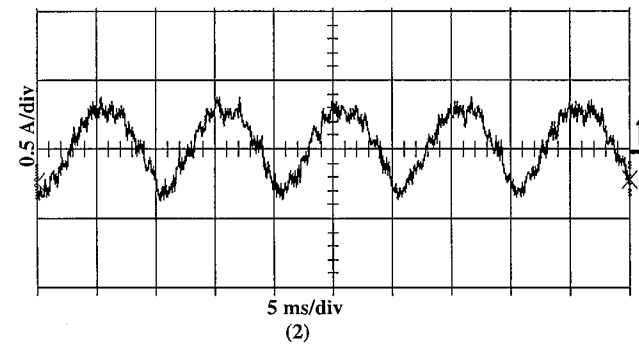
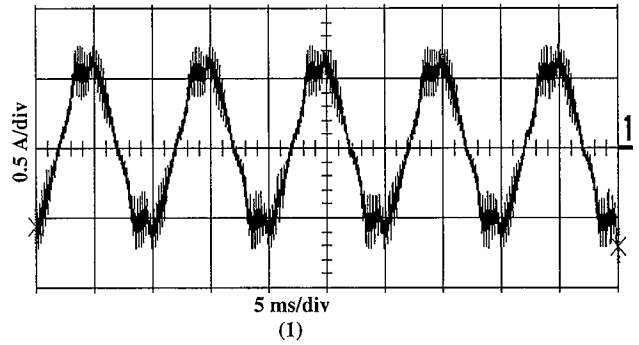
**Conclusions**

The DSP56005 based digital controller has been developed for an IVAS. Two different types of DSP systems have been produced for system development and on-line closed-loop testing for the blood pump. Two control schemes, current and speed control, have been developed and investigated, and a more effective combined control strategy is also presented. Different operation modes of the PM motor were also developed, and experimental results obtained.

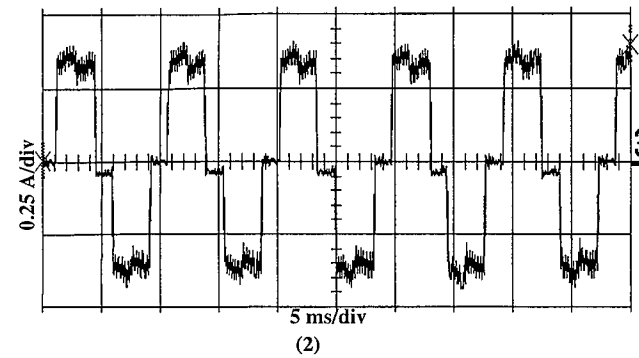
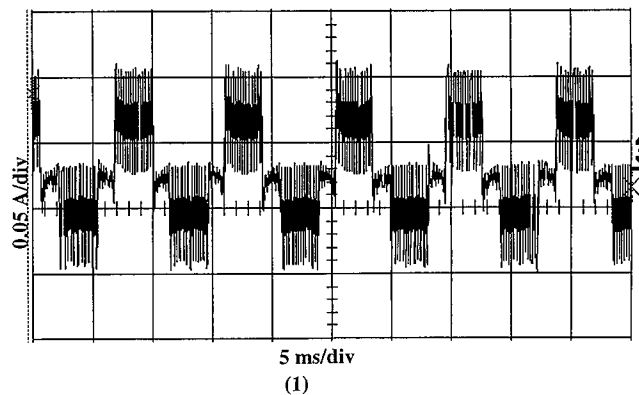
1. The DSP system has excellent arithmetic/logic calcula-



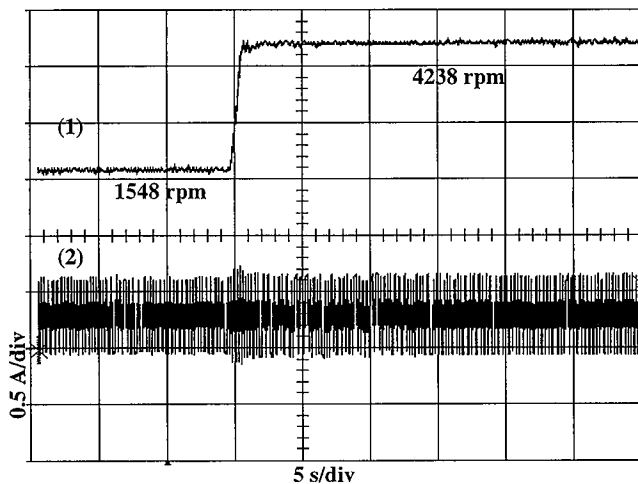
**Figure 7.** Speed and phase current of the innovative ventricular assist system motor in brushless DC motor mode. *Upper:* Speed (~3,200 r/min). *Lower:* Current.



**Figure 8.** Phase current of the innovative ventricular assist system motor in permanent magnet synchronous motor mode. (1) Open-loop without load. (2) Closed-loop with full load.



**Figure 9.** Phase current of the innovative ventricular assist system motor in brushless DC motor mode. (1) Open-loop without load. (2) Closed-loop with full load.



**Figure 10.** Speed tracking of the innovative ventricular assist system motor under full load. *Upper:* Speed response to step command. *Lower:* Phase current.

tion and interfacing capability. It is ideal to secure an efficient, compact, and reliable performance for an IVAS, with substantial dynamic response and sophisticated system communication/control capabilities.

- Two types of DSP systems—a developmental system and a stand alone type system—were developed. A prototype controller has been implemented. Further upgrade and

optimization of the system can be easily done in development mode and programmed for stand alone operation.

- Speed and current control of the IVAS system have been developed. With these control modes, the system has very high dynamic response to maintain the required pressure and flow of the pump. The combined control will make the system operate in a more reasonable and useful way. The combined characteristic can be software programmed and adjusted to different physiologic inputs.
- The IVAS motor can be driven in two ways using different current waveforms. They are PMSM with sinusoidal current and BLDC with rectangular current. Both drivers have been implemented and extensively tested. The BLDC operation has been chosen for the prototype controller for reliability reasons.

The prototype DSP controller also has expansion and flexibility features. Further optimization of the hardware and software is in progress, and bidirectional communication with physiologic and diagnostic interfaces are also to be developed.

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## *In Vitro* and *In Vivo* Evaluation of a Left–Right Balancing Capacity of an Interatrial Shunt in an Electrohydraulic Total Artificial Heart System

EISUKE TATSUMI, MAKOTO NAKAMURA, TORU MASUZAWA, YOSHIYUKI TAENAKA, YOUNG-SANG SOHN, TAKASHI NISHIMURA, MASAKO NAKATA, TAKESHI NAKATANI, TAKASHI OHNO, SEIKO ENDO, KOKI TAKIURA, YOSHIKI TAKAWA, YUKIHIDE KAKUTA, AND HISATERU TAKANO

The authors evaluated the basic performance of an interatrial shunt (IAS) made by punching a hole in the atrial septum, in accommodating the left–right imbalance in our electrohydraulic total artificial heart (EHTAH) system. In an *in vitro* study conducted in a closed mock circuit connected with the EHTAH, the interatrial pressure gradient changed in compliance with the amount of bronchial flow and the size of the

IAS. The IAS of 4.4 mm diameter or larger maintained the interatrial pressure gradient within physiologically permissible limits when the amount of bronchial flow was 5% of cardiac output or less. A left-to-right one-way valve made of a piece of pericardium, a possible option in this IAS method, successfully prevented right-to-left reverse shunt flow through the IAS. In a chronic *in vivo* study using a calf implanted with the EHTAH for 10 days, a 4.5 mm IAS without the one-way valve demonstrated satisfactory dynamic left–right balancing capacity with a stable interatrial pressure gradient of  $4 \pm 1$  mmHg over a wide range of atrial pressures. No thrombus was found in or around the IAS at autopsy. The authors conclude that the IAS is a simple and promising means

From the Department of Artificial Organs, National Cardiovascular Center Research Institute, Osaka, Japan.

Reprint requests: Eisuke Tatsumi, MD, PhD, Department of Artificial Organs, National Cardiovascular Center, Research Institute, 5-7-1 Fujishiro-dai, Suita, Osaka 565, Japan.