

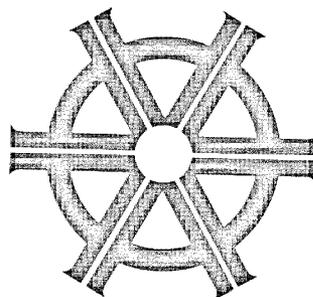
June 1996

Volume 20 • Number 6

Rotary Blood Pumps
S. Ohtsubo, J.C. Baldwin, and M.E. DeBakey
Guest Editors

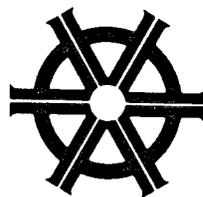
ARTIFICIAL ORGANS

Official Journal
of the International Society
for Artificial Organs



and the International Faculty for Artificial Organs

Blackwell Science, Inc.



ARTIFICIAL ORGANS

*Official Journal of the International Society for Artificial Organs
and the International Faculty for Artificial Organs*

Volume 20, Number 6
June 1996

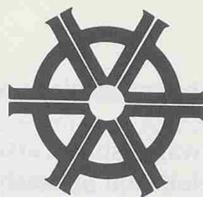
CONTENTS

- 459 Greetings from the Honorary President of the International Society for Rotary Blood Pumps
Dr. Michael E. DeBakey
- 460 Greetings from the Honorary Congress President of the International Society for Rotary
Blood Pumps
Dr. John C. Baldwin
- EDITORIAL
- 461 Evolution Toward the Development of Totally Implantable Rotary Blood Pumps
Satoshi Ohtsubo and Yukihiro Nosé
- 463 ISRP Presidential Address: Is It Really Possible To Support or Replace a Human Heart with a
Mechanical Pump—a Human Heart—with all its Historical, Philosophical and
Emotional Importance?
Ernst Wolner and Margit Kadletz
- 467 Can We Develop a Nonpulsatile Permanent Rotary Blood Pump? Yes, We Can.
Yukihiro Nosé, Koji Kawahito, and Tadashi Nakazawa
- 475 Can We Develop a Permanent Pulsatile Rotary Blood Pump? Yes, We Can.
Victor L. Poirier
- 481 The Cleveland Clinic Rotodynamic Pump Program
Leonard A. R. Golding, William A. Smith, and Douglas R. Bodman
- 485 Development of a Pivot Bearing Supported, Sealless Centrifugal Pump for Ventricular Assist
Tadashi Nakazawa, Kenzo Makinouchi, Yasuhisa Ohara, Satoshi Ohtsubo,
Koji Kawahito, Kimitaka Tasai, Takutugu Shimono, Robert Benkowski, George Damm,
Yoshiyuki Takami, Julie Glueck, George P. Noon, and Yukihiro Nosé

(continued on next page)

Listed in *Current Contents*, *Index Medicus*, *Biological Abstracts*, *Cambridge Scientific Abstracts/LSC*,
EMBASE, *Chemical Abstracts*, and *Science Citation Index*

Artificial Organs (ISSN 0160-564X) is published monthly by Blackwell Science, Inc., 238 Main Street, Cambridge, MA 02142, U.S.A. Second class postage paid at Boston, MA, and at additional mailing offices. *Subscription rates for Volume 20 (12 issues) 1996:* Personal subscriptions \$355 in U.S., \$375 in Canada and Mexico, \$395 overseas; Institutional subscriptions \$540 in U.S., \$560 in Canada and Mexico, \$580 overseas. Single copies \$50. Journal issues prior to the current volume, when available, may be ordered at the single copy rate. Air delivery is used for all countries overseas. Payment should accompany all orders. Please enclose present mailing label with all change of address requests. Address advertising and reprint/offprint inquiries to Tom Palmisano, Blackwell Science, Inc. **Claims for missing issues:** Claims for missing issues will be serviced at no charge if received within 90 days of the cover date for domestic subscribers and 6 months for subscribers outside the U.S. Duplicate copies cannot be sent to replace issues not delivered because of failure to notify publisher of change of address. **Cancellations:** If not completely satisfied, refund available on all unmailed issues. **Postmaster:** Send change of address to *Artificial Organs*, Subscription Department, Blackwell Science, Inc., 238 Main Street, Cambridge, MA 02142. Copyright © 1996 International Society for Artificial Organs.
When citing this journal, abbreviate as *Artif Organs*.



ARTIFICIAL ORGANS

*Official Journal of the International Society for Artificial Organs
and the International Faculty for Artificial Organs*

Volume 20, Number 6
June 1996

CONTENTS

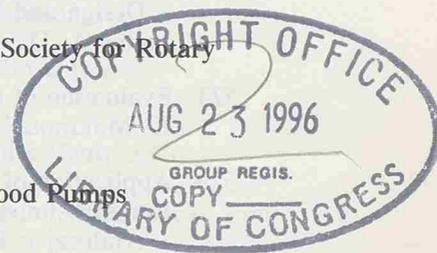
- 459 Greetings from the Honorary President of the International Society for Rotary Blood Pumps
Dr. Michael E. DeBakey
- 460 Greetings from the Honorary Congress President of the International Society for Rotary
Blood Pumps
Dr. John C. Baldwin
- EDITORIAL
- 461 Evolution Toward the Development of Totally Implantable Rotary Blood Pumps
Satoshi Ohtsubo and Yukihiko Nosé
- 463 ISRP Presidential Address: Is It Really Possible To Support or Replace a Human Heart with a
Mechanical Pump—a Human Heart—with all its Historical, Philosophical and
Emotional Importance?
Ernst Wolner and Margit Kadletz
- 467 Can We Develop a Nonpulsatile Permanent Rotary Blood Pump? Yes, We Can.
Yukihiko Nosé, Koji Kawahito, and Tadashi Nakazawa
- 475 Can We Develop a Permanent Pulsatile Rotary Blood Pump? Yes, We Can.
Victor L. Poirier
- 481 The Cleveland Clinic Rotodynamic Pump Program
Leonard A. R. Golding, William A. Smith, and Douglas R. Bodman
- 485 Development of a Pivot Bearing Supported, Sealless Centrifugal Pump for Ventricular Assist
Tadashi Nakazawa, Kenzo Makinouchi, Yasuhisa Ohara, Satoshi Ohtsubo,
Koji Kawahito, Kimitaka Tasai, Takutugu Shimono, Robert Benkowski, George Damm,
Yoshiyuki Takami, Julie Glueck, George P. Noon, and Yukihiko Nosé

(continued on next page)

Listed in *Current Contents*, *Index Medicus*, *Biological Abstracts*, *Cambridge Scientific Abstracts/LSC*,
EMBASE, *Chemical Abstracts*, and *Science Citation Index*

Artificial Organs (ISSN 0160-564X) is published monthly by Blackwell Science, Inc., 238 Main Street, Cambridge, MA 02142, U.S.A. Second class postage paid at Boston, MA, and at additional mailing offices. *Subscription rates for Volume 20 (12 issues) 1996:* Personal subscriptions \$355 in U.S., \$375 in Canada and Mexico, \$395 overseas; Institutional subscriptions \$540 in U.S., \$560 in Canada and Mexico, \$580 overseas. Single copies \$50. Journal issues prior to the current volume, when available, may be ordered at the single copy rate. Air delivery is used for all countries overseas. Payment should accompany all orders. Please enclose present mailing label with all change of address requests. Address advertising and reprint/offprint inquiries to Tom Palmisano, Blackwell Science, Inc. **Claims for missing issues:** Claims for missing issues will be serviced at no charge if received within 90 days of the cover date for domestic subscribers and 6 months for subscribers outside the U.S. Duplicate copies cannot be sent to replace issues not delivered because of failure to notify publisher of change of address. **Cancellations:** If not completely satisfied, refund available on all unmailed issues. **Postmaster:** Send change of address to *Artificial Organs*, Subscription Department, Blackwell Science, Inc., 238 Main Street, Cambridge, MA 02142. Copyright © 1996 International Society for Artificial Organs.

When citing this journal, abbreviate as *Artif Organs*.



CONTENTS

- 491 **Development of a Centrifugal Pump with Improved Antithrombogenicity and Hemolytic Property for Chronic Circulatory Support**
Yoshiyuki Taenaka, Yoshinari Wakisaka, Toru Masuzawa, Eisuke Tatsumi, Koichi Toda, Koji Miyazaki, Kazuhiro Eya, Yuzo Baba, Takeshi Nakatani, Takashi Ohno, Takashi Nishimura, and Hisateru Takano
- 497 **A Ferrofluidic Seal Specially Designed for Rotary Blood Pumps**
Yoshinori Mitamura, Masayoshi Fujiyoshi, Toshiobu Yoshida, Ryohei Yozu, Eiji Okamoto, Takashi Tanaka, and Shiaki Kawada
- 503 **Findlay Two-Stage Implantable Centrifugal Pump**
Peter V. Moulder, Iain S. Findlay, Robert M. Zone, Jr., Arnold J. Thompson, Harry A. Silber, William R. Rank, Michael D. Charbonnet, Watts R. Webb, and Lynn H. Harrison
- 513 **Wear-Resistant, Hemocompatible Ti-Nb-Zr and Zr-Nb Alloys that Improve Blood Pump Design and Performance**
James A. Davidson, Kenneth P. Daigle, and Paul Kovacs
- 523 **Evaluation of the Wear of the Pivot Bearing in the Gyro Pump C1E3**
K. Makinouchi, T. Nakazawa, Y. Takami, S. Takatani, and Y. Nosé
- 529 **Application of Computational Fluid Dynamics Techniques to Blood Pumps**
Ramakrishnan Sukumar, Mahesh M. Athavale, Vinod B. Makhijani, and Andrej J. Praekwas
- 534 **High-Resolution Fluorescent Particle Tracking Flow Visualization With an Intraventricular Axial Flow Left Ventricular Assist Device**
John P. Kerrigan, Kenji Yamazaki, Rebecca K. Meyer, Toshio Mori, Yasuo Otake, Eisuke Outa, Mitsuo Umezu, Harvey S. Borovetz, Robert L. Kormos, Bartley P. Griffith, Hitoshi Koyanagi, and James F. Antaki
- 541 **Study of Secondary Flow in Centrifugal Blood Pumps Using a Flow Visualization Method with a High-Speed Video Camera**
Ichiro Sakuma, Yasuhiro Fukui, and Takeyoshi Dohi
- 546 **Estimating Mechanical Blood Trauma in a Centrifugal Blood Pump: Laser Doppler Anemometer Measurements of the Mean Velocity Field**
Marcos Pinotti and Nicola Paone
- 553 **Prediction of Hemolysis in Turbulent Shear Orifice Flow**
Masaaki Tamagawa, Teruaki Akamatsu, and Keijiroh Saitoh
- 560 **Comparative Hemolysis Study of Clinically Available Centrifugal Pumps**
Kozo Naito, Etsuro Suenaga, Zhi-Li Cao, Hisao Suda, Tetsuya Ueno, Masafumi Natsuaki, and Tsuyoshi Itoh
- 564 **Relationship Between Pump Speed Design and Hemolysis in an Axial Flow Blood Pump**
Hirofumi Anai, Yoshinari Wakisaka, Takeshi Nakatani, Yoshiyuki Taenaka, Hisateru Takano, and Tetsuo Hadama

Artificial Organs is registered with the Copyright Clearance Center, Inc., 222 Rosewood Drive, Suite 910, Danvers, MA 01923, U.S.A. Consent is given for copying articles for personal use, but copying beyond that permitted by Sections 107 and 108 of the U.S. Copyright Law is subject to payment of a base fee of \$10.50 per copy of the article paid directly to the Copyright Clearance Center at the above address. This consent does not extend to copying for general distribution, resale, advertising, and promotion, or for creating new collective works. 0160-564X/96 \$10.50.

Blackwell Science, Inc. and the International Society for Artificial Organs cannot be held responsible for errors or for any consequences arising from the use of the information contained in this journal. The appearance of advertising in this journal does not constitute an endorsement or approval by Blackwell Science, Inc. or the Society for the quality or value of the product advertised or of the claims made for it by its manufacturer.

- 568 **New Method of Evaluating Sublethal Damage to Erythrocytes by Blood Pumps**
Takatsugu Shimono, Kenzo Makinouchi, Isao Yada, and Yukihiko Nosé
- 572 **Tandem Operation of a Turbo Blood Pump (BP-80-Type Centrifugal Pump) to Reduce Hemolysis**
Y. Wakisaka, Y. Taenaka, T. Nakatani, H. Anai, K. Araki, T. Nishimura, E. Tatsumi, T. Masuzawa, Y. Baloa, K. Toda, K. Eya, K. Miyazaki, Y. Takewa, and H. Takano
- 575 **Effects of Surface Roughness on Mechanical Hemolysis**
Mitsuo Umezu, Takashi Yamada, Hiromi Fujimasu, Tetsuo Fujimoto, Manoja Ranawake, Atsuhiko Nagawa, and Toshihiko Kijima.
- 579 **Comparison of Centrifugal and Roller Pump Hemolysis Rates at Low Flow**
Yuko S. Moon, Satoshi Ohtsubo, Michael R. Gomez, Jon K. Moon, and Yukihiko Nosé
- 582 **Prototype Continuous Flow Ventricular Assist Device Supported on Magnetic Bearings**
P. E. Allaire, H. C. Kim, E. H. Maslen, D. B. Olsen, and G. B. Bearnson
- 591 **A Magnetically Suspended and Hydrostatically Stabilized Centrifugal Blood Pump**
Robert M. Hart, Victor G. Filipenco, and Robert T. V. Kung
- 597 **Using Hybrid Magnetic Bearings to Completely Suspend the Impeller of a Ventricular Assist Device**
Pratap Khanwilkar, Don Olsen, Gill Bearnson, Paul Allaire, Eric Maslen, Ron Flack, and James Long
- 605 **Characteristics of a Blood Pump Combining the Centrifugal and Axial Pumping Principles: The Spiral Pump**
Aron Andrade, José Biscegli, Jarbas Dinkhuysen, José Eduardo Sousa, Yukio Ohashi, Sarah Hemmings, Julie Glueck, Koji Kawahito, and Yukihiko Nosé
- 613 **A Teaspoon Pump for Pumping Blood with High Hydraulic Efficiency and Low Hemolysis Potential**
Don Dame
- 618 **Controller for an Axial Flow Blood Pump**
Hiroaki Konishi, James F. Antaki, Devin V. Amin, J. R. Boston, John P. Kerrigan, William A. Mandarin, Philip Litwak, Kenji Yamazaki, Mahender Macha, Kenneth C. Butler, Harvey S. Bororetz, and Robert L. Kormos
- 621 **Transcutaneous Energy Transfer with Voltage Regulation for Rotary Blood Pumps**
Tofy Mussivand, Kevin S. Holmes, Albert Hum, and W. J. Keon
- 625 **Clinical Application of a Newly Developed Autoflow Control System for the Terumo Centrifugal Pump: From External Control to Built-in Direct Control**
Hiroshi Nishida, Tomohiro Nishinaka, Masahiro Endo, Hiroshi Koyanagi, Hiroaki Oshiyama, Atsuhiko Nogawa, and Tetsuzo Akutsu
- 632 **Numerical Simulation of Nonpulsatile Left Ventricular Bypass**
Norimasa Mitsui, Shintaro Fukunaga, Yoshihiko Koura, Satoru Morita, Hiroshi Hotei, Masafumi Sueshiro, Taijiro Sueda, and Yuichiro Matsuura
- 637 **Fluctuations of the Hemodynamic Derivatives During Left Ventricular Assistance Using Oscillate Blood Flow**
Tomoyuki Yambe, Shin-ichi Kobayashi, Shusuke Nanke, Shigeru Naganuma, Shin-ichi Nitta, Hidetoshi Matsuki, Ken-ichi Abe, Makoto Yoshizawa, Takeo Fukuju, Kou-ichi Tabayashi, Hiroshi Takeda, and Hiroyuki Hashimoto
- 641 **The Heart-Hemopump Interaction: A Study of Hemopump Flow as a Function of Cardiac Activity**
B. Meyns, T. Siess, S. Laycock, H. Reul, G. Rau, and W. Flameng

- 650 **Hemodynamic System Analysis of Intraarterial Microaxial Pumps In Vitro and In Vivo**
Thorsten Siess, Bart Meyns, Klaus Spielvogel, Helmut Ruel, Günter Rau, and Willem Flameng
- 662 **Subchronic Use of the St. Jude Centrifugal Pump as a Mechanical Assist Device in Calves**
Jack J. Curtis, Colette C. Wagner-Mann, Fred A. Mann, Todd L. Demmy, Joseph Walls, and James R. Turk
- 666 **Subchronic Centrifugal Mechanical Assist in an Unheparinized Calf Model**
Colette C. Wagner-Mann, Jack J. Curtis, Fred A. Mann, James R. Turk, Todd L. Demmy, Timothy Turpin
- 670 **A Calf Model for Left Ventricular Centrifugal Mechanical Assist**
A. Mann, Colette C. Wagner-Mann, Jack J. Curtis, Todd L. Demmy, and James R. Turk
- 678 **Coronary Microcirculation During Left Heart Bypass with a Centrifugal Pump**
Mitsumasa Hata, M. Shiono, Y. Orime, K. Nakata, A. Sezai, H. Yamada, T. Saito, and Y. Sezai
- 681 **Effect of Pulsatile and Nonpulsatile Assist on Heart and Kidney Microcirculation with Cardiogenic Shock**
Kinichi Nakata, Motomi Shiono, Yukihiko Orime, Mitumasa Hata, Akira Sezai, Toshimi Saitoh, and Yukiyasu Sezai
- 685 **Pharmacologically Induced Heart Failure for the Evaluation of Circulatory Assistance**
C. Schmidt, I. Schwendenwein, G. Wieselthaler, K. Roschal, H. Schima, U. Losert, and E. Wolner
- 689 **Basic Performance of a Miniature Intraventricular Axial Pump**
Mitsuo Umezu, Yasuo Ohtake, Koji Sakata, Tetsuo Fujimoto, Kenji Yamazaki, Hitoshi Koyanagi, Haruo Iiyama, Toshio Mori, and Kenji Higuchi
- 694 **Role of the BioMedicus Pump and Distal Aortic Perfusion in Thoracoabdominal Aortic Aneurysm Repair**
Hazim J. Safi
- 700 **A New Supportive Method for Aortic Aneurysm Surgery: Centrifugal Left Heart Bypass Combined with an Oxygenator and a Heat Exchanger**
Shigeyuki Aomi, Akimasa Hashimoto, Osamu Tagusari, Hiroshi Nishida, Minoru Nomura, Izumi Kondah, Keiko Kodaka, and Hitoshi Koyanagi
- 704 **Clinical Use of Centrifugal Pumps and the Roller Pump in Open Heart Surgery: A Comparative Evaluation**
Masaru Yoshikai, Masakatsu Hamada, Kyoumi Takarabe, Yukio Okazaki, and Tsuyoshi Ito
- 707 **Less Blood Damage in the Impeller Centrifugal Pump: A Comparative Study with the Roller Pump in Open Heart Surgery**
Tomohiro Nishinaka, Hiroshi Nishida, Masahiro Endo, Masayuki Miyagishima, Goro Ohtsuka, and Hitoshi Koyanagi
- 711 **Clinical Experience with the Nikkiso Centrifugal Pump**
Yo Shomura, Takatsugu Shimono, Koji Onoda, Iwao Hioki, Hironori Tenpaku, Yasumi Maze, Toru Mizumoto, Kazuhiro Tani, Kuniyoshi Tanaka, Hideto Shimpo, Hiroshi Yuasa, and Isao Yada
- 715 **Clinical Comparative Study of Cardiopulmonary Bypass with Nikkiso and BioMedicus Centrifugal Pumps**
Satoshi Ohtsubo, Eiki Tayama, David Short, George P. Noon, and Yukihiko Nosé

- 721 **Experiences of Postcardiotomy Assist: Pneumatic Ventricular Assist Device or Venoarterial Bypass with Percutaneous Cardiopulmonary Support**
Yukihiko Orime, Shoji Shindo, Motomi Shiono, Hiroaka Hata, Shinya Yagi,
Saeki Tsukamoto, Haruhiko Okumura, and Yukiyasu Sezai
- 724 **Biventricular Bypass with Oxygenation for Postcardiotomy Ventricular Failure**
Kohjiro Kodera, Masaya Kitamura, Mitsuhiro Hachida, Masahiro Endo,
Akimasa Hashimoto, and Hitoshi Koyanagi
- 728 **Extracorporeal Membrane Oxygenation as a Bridge to Cardiac Transplantation in Children**
Kozo Ishino, Yuguo Weng, Vladimir Alexi-Meskishvili, Matthias Loebe,
Frank Uhlemann, Peter E. Lang, and Roland Hetzer
- 733 **Clinical Experience of Percutaneous Cardiopulmonary Support**
Yoshikado Sasako, Takeshi Nakatani, Hiroshi Nonogi, Shunichi Miyazaki,
Yoshitugu Kito, Hisateru Takano, and Yasunaru Kawashima

COMMUNICATIONS

- 737 **Summary of the Third Congress of the International Society for Rotary Blood Pumps,
Houston, Texas, U.S.A., 1995**
Satoshi Ohtsubo
- 739 **Upcoming Meetings**

Controller for an Axial Flow Blood Pump

*Hiroaki Konishi, *†James F. Antaki, *†Devin V. Amin, †J.R. Boston,
†John P. Kerrigan, †William A. Mandarino, *Philip Litwak, *Kenji Yamazaki,
*Mahender Macha, ‡Kenneth C. Butler, *†Harvey S. Borovetz, and
*Robert L. Kormos

*University of Pittsburgh, Artificial Heart and Lung Program, Schools of *Medicine and †Engineering, Pittsburgh, Pennsylvania; and ‡Nimbus, Inc., Rancho Cordova, California, U.S.A.*

Abstract: A rotary blood pump inherently provides only one noninvasive "observable" parameter (motor current) and allows for only one "controllable" parameter (pump speed). To maintain the systemic circulation properly, the pump speed must be controlled to sustain appropriate outlet flows and perfusion pressure while preventing pulmonary damage caused by extremes in preload. Steady-state data were collected at repeated intervals during chronic trials of the Nimbus AxiPump (Nimbus, Inc., Rancho Cordova, California, U.S.A.) in sheep ($n = 7$) and calves ($n = 12$). For each data set, the pump speed was increased at increments of 500 rpm until left ventricular and left atrial emptying was observed by left atrial pressure diminishing to zero. The effect of decreasing

preload was evaluated perioperatively by inferior vena cava occlusion at a constant pump speed. Fourier analysis established a relationship between changes in the pump preload and the power spectra of the pump current waveform. Based on these results, a control method was devised to avoid ventricular collapse and maintain the preload within a physiologic range. The objective of this controller is the minimization of the second and third harmonic of the periodic current waveform. This method is intended to provide a noninvasive regulation of the pump by eliminating the need for extraneous transducers. **Key Words:** Axial flow blood pump—Noninvasive pump regulation.

The axial flow blood pump design has numerous advantages for the next generation of left ventricular assist devices (LVAD): small size, high efficiency, and simplicity of implantation (1). These and other advantages are bought at the expense of inherently greater demand for external control. Unlike their positive displacement counterparts, these devices intrinsically provide only one observable parameter, pump current, and one controllable parameter, pump speed. The characteristic performance of this class of pumps dictates that flow and differential pressure are interdependent. Therefore, it is difficult to control pump flow without flow sensor feedback, or knowledge of afterload or differential pressure (2). To overcome this difficulty, we are attempting to develop a control algorithm based

exclusively on the time-varying electrical power drawn by the pump motor (3,4).

MATERIALS AND METHODS

An axial flow blood pump (AxiPump; Nimbus, Inc., Rancho Cordova, California, U.S.A.) was implanted in 7 sheep weighing 60–80 kg and in 12 calves weighing 90–110 kg in chronic preparations for 7 to 150 days. The inflow cannula was inserted into the left ventricular apex, and the outflow graft was anastomosed to the descending aorta. Pump flow was obtained by a customized ultrasonic flow probe (Transonic Systems, Inc., Ithaca, New York, U.S.A.) incorporated into the urethane portion of the outflow graft. The pump was placed at the abdominal wall under the muscle. The drive line was connected percutaneously to the drive console, which could vary the pump speed from 6,000 rpm to 13,000 rpm.

Aortic blood pressure (AoP), left atrial pressure

Received January 1996.

Address correspondence and reprint requests to Dr. Robert L. Kormos, at Division of Cardiothoracic Surgery, University of Pittsburgh Medical Center, Suite C-700, Presbyterian University Hospital, Lothrop Street, Pittsburgh, PA 15213, U.S.A.

(LAP), central venous pressure (CVP), pump speed, and pump motor current were collected at 150 Hz on a computer workstation (Apollo, DN3550; Hewlett Packard, Inc. Chelmsford, Massachusetts, U.S.A.). During each data collection, the pump speed was increased at 500 rpm increments from 8,000 rpm to 13,000 rpm. In 3 of these cases, the inferior vena cava (IVC) was occluded gradually before chest closure to decrease the preload of the pump for 15 s.

RESULTS

Figure 1 shows typical hemodynamic changes observed while the pump speed was increased. Mean AoP increased slightly, and the increase in diastolic pressure was higher than the increase in systolic pressure. Accordingly, the pulse pressure decreased from 40 mm Hg to less than 15 mm Hg. When the pump speed was maximized, collapse of the left ventricle occurred, and the AoP was observed to fluctuate aperiodically. Concurrently, LAP decreased and evidenced an abrupt onset of oscillation as the left atrium was observed to collapse. Continuous or prolonged operation under these conditions, leading to negative LAP and damage to the pulmonary circulation, must be avoided. At the lower extreme, when pump speed was reduced excessively, the flow trace displayed regurgitation from the aorta to the left ventricle during ventricular diastole. Within the preferred operating speed range, the "optimal point", there is no evidence of negative flow.

The shape of the pump motor current waveform was seen to display characteristic changes that were dependent on the pump speed and preload (Fig. 2).

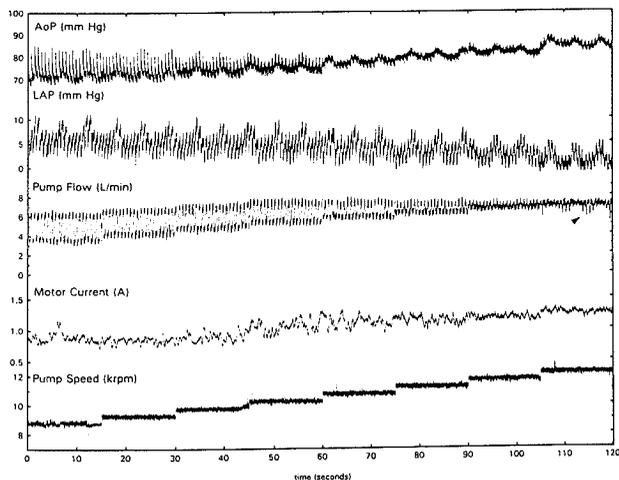


FIG. 1. Hemodynamic changes while the pump speed was increased. AOP, aortic blood pressure; LAP, left atrial pressure. The arrow indicates ventricular collapse.

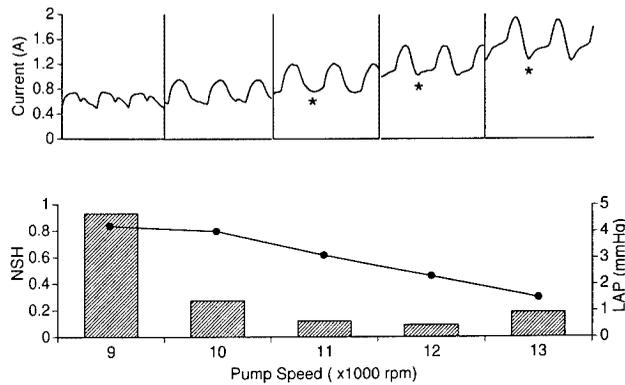


FIG. 2. The pump motor current waveform and the relationship between NSH and LAP are shown. NSH, normalized second harmonic.

A relationship was determined to exist between the optimal pump speed and the normalized second harmonic, defined as the ratio of the second harmonic to the first harmonic (normalized second harmonic [NSH]). The relationship between the NSH and LAP typically revealed a unimodal behavior with a single minimum coinciding with the minimum LAP. This result would imply that if the pump speed is maintained at the point at which the NSH value is minimal, the ventricle and atrium do not collapse and LAP can be maintained within the lower side of its physiologic range.

Figure 3 shows the results during IVC occlusion. During the occluding phase, the LAP and AoP decreased rapidly, and the current waveform became erratic, changing beat by beat. However, during the recovery phase, the preload of the pump returned slowly to physiologic range, thereby displaying the damped response of the current waveform to the changing preload.

DISCUSSION

In developing an axial flow blood pump as an implantable LVAD, long-term survival has been ob-

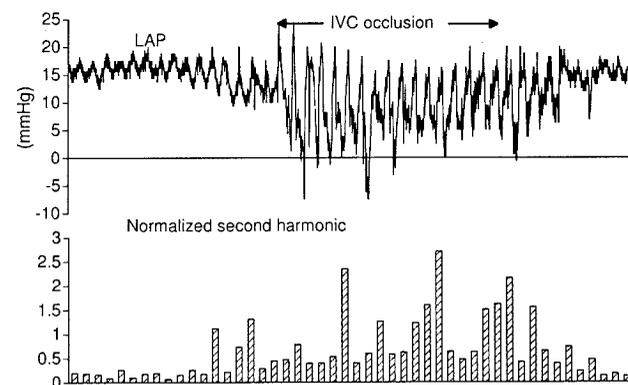


FIG. 3. Results of the inferior vena cava occlusion test are shown. IVC, inferior vena cava.

tained in animals (5). However, there still is no systematic algorithm to control these types of pumps in the chronic setting. Dynamically characterizing the relationship among pump flow, pressure increase, and speed would provide an improved opportunity to control speed for optimal hemodynamics. Although the quasi-static H-Q response of these pumps usually is well defined, the effect of pulsatile hemodynamics introduces significant hysteresis and nonuniqueness (6) (Fig. 4). Accordingly, the ability to identify flow or pressure from speed or motor current becomes much more difficult, if not impossible. In the next-generation controller, to maintain normal hemodynamics under the wide range of conditions expected, pump flow must be adjusted rapidly to accommodate physiologic demand. Because the pump speed is not inherently sensitive to changes in the preload or afterload, the ventricle and atrium will collapse if the pump speed is too high. If the pump speed is too low, regurgitation occurs from the aorta into the left ventricle during ventricular diastole (Fig. 5). Detection of the minimum NSH is one of the noninvasive methods used to avoid these situations. To improve the reliability of the detection of the minimum NSH, it is necessary to obtain a stable motor current signal. In the development of the next stage of this controller, the algorithm used to seek the minimum NSH continuously must be developed. In the second-generation controller, the flow estimation will be derived from the motor current. This work includes

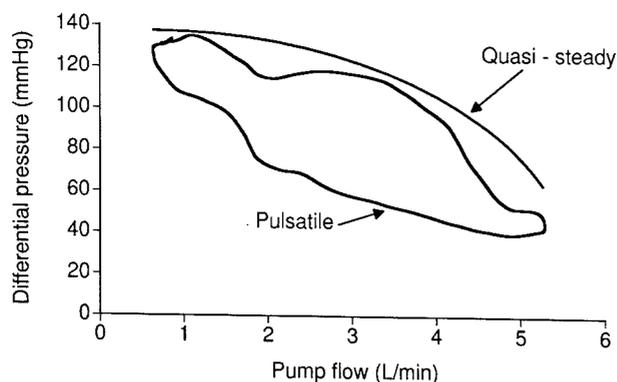


FIG. 4. Pump performance (H-Q curve) (Pump speed = 10 Krpm) is shown.

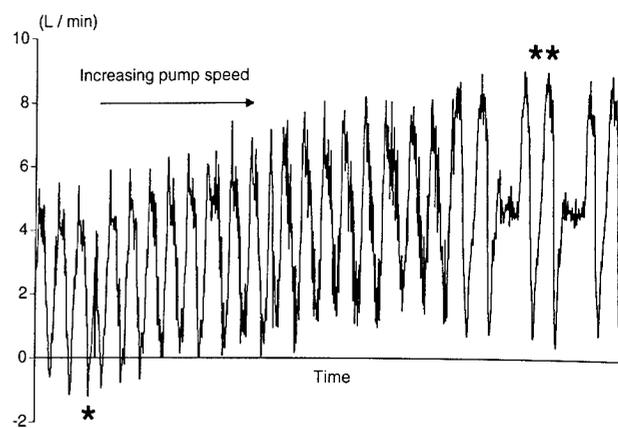


FIG. 5. Pump flow while the pump speed was increased is shown. *, regurgitation from the aorta into the left ventricle; **, collapse of the left ventricle or atrium.

the application of matched filters to analyze the overall waveform characteristics. Ongoing work to make the control algorithm more robust and enable the control structure to be tuned or adapted to individual patients is another part of this ongoing effort.

REFERENCES

1. Antaki JF, Butler KC, Kormos RL, Kawai A, Konishi H, Kerrigan JP, Borovetz HS, Maher TR, Kamenewa MV, Griffith BP. In vivo evaluation of the Nimbus axial flow ventricular assist system: criteria and methods. *Am Soc Artif Intern Organs* 1993;39:M231-M236.
2. Schima H, Trubel W, Moritz A, Wieselthaler G, Stohr HG, Thoma H, Losert U, Wolner E. Noninvasive monitoring of rotary blood pumps: necessity, possibilities, and limitations. *Am Soc Artif Intern Organs* 1992;16(2):195-202.
3. Konishi H, Antaki JF, Boston JR, Borovetz HS, Kerrigan JP, Mandarino WA, Butler KC, Kormos RL. Controller for an axial flow blood pump LVAD. *Am Soc Artif Intern Organs* 1994;23:35.
4. Trinkl J, Havlik P, Mesana T, Mitsui N, Morita S, Demunck J-L, Tourres J-L, Monties J-R. Control of a rotary pulsatile cardiac assist pump driven by an electric motor without a pressure sensor to avoid collapse of the pump inlet. *Am Soc Artif Intern Organs* 1993;39:M237-M241.
5. Macris MP, Myers TJ, Jarvik R, Robinson JL, Fuqua JM, Parnis SM, Frazier OH. In vivo evaluation of an intraventricular electric axial flow pump for left ventricular assistance. *Am Soc Artif Intern Organs* 1994;40:M719-M722.
6. Yamazaki K, Umezu M, Koyanagi H, Outa E, Ogino S, Otake Y. Development of a miniature intraventricular axial flow blood pump. *Am Soc Artif Intern Organs* 1993;39:M224-M230.